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Citation for published version:
Stuart, N 2015, 'ArcGeomorphometry: A toolbox for geomorphometric characterization of DEMs in the ArcGIS environment', *Computers and Geosciences*. https://doi.org/10.1016/j.cageo.2015.09.020

Digital Object Identifier (DOI):
10.1016/j.cageo.2015.09.020

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Computers and Geosciences

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Download date: 26. Apr. 2024

ArcGeomorphometry: A toolbox for geomorphometric characterization of DEMs in the ArcGIS environment

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Abstract

A software tool is described for the extraction of geomorphometric land surface variables and features from Digital Elevation Models (DEMs). The ArcGeomorphometry Toolbox consists of a series of Python/Numpy processing functions, presented through an easy-to-use graphical menu for the widely used ArcGIS package. Although many GIS provide some operations for analysing DEMs, the methods are often only partially implemented and can be difficult to find and used effectively. Since the results of automated characterisation of landscapes from DEMs are influenced by the extent being considered, the resolution of the source DEM and the size of the kernel (analysis window) used for processing, we have developed a tool to allow GIS users to flexibly apply several multi-scale analysis methods to parameterise and classify a DEM into discrete land surface units. Users can control the threshold values for land surface classifications. The size of the processing kernel can be used to identify land surface features across a range of landscape scales. The pattern of land surface units from each attempt at classification is displayed immediately and can then be processed in the GIS alongside additional data that can assist with a visual assessment and comparison of a series of results. The functionality of the ArcGeomorphometry toolbox is described using an example DEM.

Keywords: Geomorphometry; DEM; GIS; Python; Numpy; Digital Terrain Analysis.

1. Introduction

The analysis and classification of the land surface at various landscape scales is a prerequisite for many studies within the geosciences. In the last two decades geomorphometry – the discipline of quantitative land-surface analysis – has undergone rapid progress due to the flexibility and rapidity with which the required computations can now be performed through the computerized analysis of digital elevation models (DEMs) (Pike, 2000; Pike et al., 2009). DEM analysis is now used to characterise and to extract relevant landscape features in fields as diverse as geomorphology, surface hydrology, visual impact assessment, watershed management, land management, cellular telecommunications, civil engineering, oceanography, ecology, soil science, planetary science, wind energy planning. The almost global coverage of gridded DEMs at resolutions between 30-90m, from sources such as the ASTER Global Digital Elevation Model (GDEM) and the Shuttle Radar Topographic Mission (SRTM) has renewed interest in semi-automatic methods for the characterisation of contrasting landscapes and for consistently identifying what Lueder (1959) defines as second-order of relief features such as mountain ranges and plains and third-order relief features such as individual hills, mountains and valleys.

Although the basic DEM processing can be conducted almost automatically, there is still a need for user interaction at various stages, for example to review the effects of different analyses and parameterisations, to compare the results of alternative landscape segmentations and classifications and to interpret and to contextualize the results, especially when performed at multiple scales. The ability to visually explore and compare many results along with the availability of faster and friendlier GIS toolboxes have been recognised as important new developments in geomorphometry software (Wood, 2009a; Gessler et al., 2009). Gessler et al. (2009) have identified a number of topics needing research in the field of geomorphometry. They include, among others, algorithm development for true multi-scale characterisation, maintaining operational ease of use despite increasing complexity of morphometric procedures, and tools for static and dynamic visualisation of measures and surface objects. Consequently, there is a need for multi-scale land surface analysis and visualization tools that facilitate common tasks such as performing multi-scale analyses and exploring the results of using different analysis window sizes and classification parameters and hence finding appropriate settings for identifying landscape characteristics and specific geomorphometric features.

Previously, the analysis of DEMs was usually conducted using specialist, stand-alone software programs. However, the widespread adoption of GIS in academic, professional and commercial arenas, the increased processing power of these systems for handling and visualising DEMs and the large volumes of spatial information now available in GIS formats are practical drivers for greater land surface analysis functionality to be included within GIS. As one means of achieving this, we present here the ArcGeomorphometry tools for geomorphometric characterisation of DEMs in the ArcGIS environment. The tools are implemented in Python/Numpy and enable a wide range of analyses to be conducted efficiently on DEMs. To understand the range of methods presently supported, the more common digital methods for land surface analysis are briefly reviewed. The functionality of the ArcGeomorphometry toolbox is then presented and compared to other existing software to locate it between the more comprehensive, specialist tools and the more limited functionality found in commercial GIS. The key features and operations of ArcGeomorphometry are described and illustrated using an example DEM. Conclusions are then drawn about the utility of the ArcGeomorphometry tools and scope for its further enhancement indicated.

2. The analysis of the land surface using digital methods

Geomorphometry is the science of quantitative land-surface analysis (Pike, 1995). Information produced by geomorphometry supports the study of many earth surface processes where landforms act as a controlling or boundary condition (Dehn et al., 2001). Applicable at different scales, geomorphometric analysis can range from the identification of localised landforms through to the characterisation of extensive regional or continental landscapes (Pike, 2000). This leads to the important distinction between specific and general geomorphometry (Evans, 1972). While specific geomorphometry analyses the geometric and topological characteristics of 'landforms' (i.e. bounded segments of a land surface that are discrete and may be discontinuous), general geomorphometry analyses 'land surface form' (i.e. a continuous field that covers the whole globe) (Evans, 2012). Thus, the related variables are object-based and field-based (see Evans and Minar, 2011, for a comprehensive classification of the fundamental variables).

A variety of equations have been proposed to calculate the fundamental geomorphometric variables. Well known examples include Evans (1972, 1979, 1980), Band (1986), Jenson and Domingue (1988), Pennock et al. (1987), Zevenbergen and Thorne (1987), Dikau (1989), Moore et al. (1993), Shary (1995), Wood (1996), Florinsky (1998), Wilson and Gallant (2000), Shary et al. (2002) and Schmidt et al. (2003). The present study is focused on the algorithms for the calculation of field local variables, therefore methods for calculating object and regional variables (e.g stream order, distance to stream, catchment area) are not discussed here. In this regard Evans' approach is the most widely used method in relation to field local variables.

Evans' method is based on fitting a second-order polynomial function to elevation in a central point and its neighbours and then deriving local gradient and curvatures (mutually orthogonal — profile and plan curvatures, and minimum and maximum curvatures) from the function:

$$z = ax^2 + by^2 + cxy + dx + ey + f \qquad (1)$$

where a to f are quadratic coefficients, x and y are local spatial coordinates, and z is elevation. Gradient and curvatures (*[L^{-1}]*) can be derived as (Evans, 1972, 1979, 1980; Schmidt et al., 2003):

$$G = (d^2 + e^2)^{1/2} \qquad (2)$$

$$C_p = -\frac{ad^2 + 2cde + be^2}{(d^2 + e^2)(1 + d^2 + e^2)^{3/2}} \qquad (3)$$

$$C_c = -\frac{ae^2 - 2cde + bd^2}{(d^2 + e^2)^{3/2}} \qquad (4)$$

$$C_{p-\min} = -a - b - ((a-b)^2 + c^2)^{1/2} \qquad (5)$$

$$C_{p-\max} = -a - b + ((a-b)^2 + c^2)^{1/2} \qquad (6)$$

where G is gradient, C_p is profile curvature, C_c is contour curvature, C_{p-min} is minimum profile curvature, and C_{p-max} is maximum profile curvature.

Several extensions to Evans' method have been proposed (Zevenbergen and Thorne, 1987; Shary, 1995; Wood, 1996; Shary et al., 2002). Zevenbergen and Thorne (1987) extended Evans' method for estimating land surface slope gradient and curvature by fitting a (partial) fourth-order polynomial surface to elevation values within a processing 3×3 window centred on a particular cell of a DEM. Shary (1995) extended Evans's method and proposed several new curvature measures, distinguishing those that depend on gravity (i.e. slope) (e.g. rotor, difference curvature) from those that are independent of slope and are derived using only surface geometry (e.g. unsphericity,). Shary (1995) used a quadratic polynomial function and a linear equation system as Evans (1980) but forced the locally interpolated surface to match the elevation of the central point of the 3×3 window centred at a particular cell (Schmidt et al., 2003). These measures can be derived from Eq. (1) as (see Shary, 1995, Shary et al., 2002, and Schmidt et al., 2003, for a complete set of formulae):

$$C_f = \frac{c(d^2 - e^2) - de(a-b)}{(d^2+e^2)^{3/2}} \qquad (7)$$

$$C_m = -\frac{a(1+e^2) - 2cde + b(1+d^2)}{2(1+d^2+e^2)^{3/2}} \qquad (8)$$

$$C_g = -\frac{ab - c^2}{(1+d^2+e^2)^2} \qquad (9)$$

$$C_{tr} = \frac{c(d^2 - e^2) - de(a-b)^2}{(d^2+e^2)^2(1+d^2+e^2)^2} \qquad (10)$$

$$C_{tot} = a^2 + 2c^2 + b^2 \qquad (11)$$

$$C_t = -\frac{ae^2 - 2cde + bd^2}{(d^2+e^2)(1+d^2+e^2)^{1/2}} \qquad (12)$$

where C_f is flowpath curvature or *rotor*, C_m is mean curvature, C_g is total Gaussian curvature, C_{tr} is total ring curvature, C_{tot} is total curvature, and C_t is tangential curvature. Other proposed curvature measures can be derived combining curvatures (3) to (12) above. Shary et al. (2002) also proposed a pre-filtering for Evans algorithm for curvature calculation that does not emphasize grid directions, which they termed *modified Evans–Young* algorithm.

Wood (1996) extended Evans' method and defined longitudinal curvature and cross-sectional curvature. These measures can be derived from Eq. (1) as:

$$C_l = -\frac{ad^2 + 2cde + be^2}{(d^2+e^2)} \qquad (13)$$

$$C_s = -\frac{ae^2 - 2cde + bd^2}{(d^2+e^2)} \qquad (14)$$

where C_l is longitudinal curvature, C_s is cross-sectional curvature, and *a* to *f* are quadratic coefficients as above. Note that Eq. (13) and (14) are those rewritten by Schmidt et al. (2003) for uniformity of equations (2) to (14) (cf. Wood, 1996; curvature measures of dimension [L^{-1}]). Schmidt et al. (2003) reviewed and compared the algorithms for land surface curvature calculation proposed by Evans (1980), Zevenbergen and Thorne (1987) and Shary (1995). They concluded that a local surface representation derived from quadratic models ('Evans' and 'Shary') is more useful to consistently describe local surface curvature, and to model the land surface by basic land elements.

Wood (1996) made an important contribution to multi-scale geomorphometric analysis by implementing a generalisation of Evans' approach to broader operational scales. Evans' original approach was limited to computing local slope gradient and curvature of land surface by analysing only the cell values within a 3×3 window (or kernel) of neighbouring cells. In high resolution (e.g. <5 m peg spacing) DEMs, this may detect only micro-scale anomalies in the land surface. MacMillan and Shary (2009) concluded that it is not possible to select any single fixed dimension for a moving window that will perfectly capture the wavelength of all landform features of interest in any given area. However, most geomorphometric variables are calculated by moving a 3×3 window across a DEM and calculating the values for the central cell in the window (Pike et al., 2009; Dragut and Eisank, 2011; Wilson, 2012). For instance, curvature values are typically computed within a 3×3 window, but clear advantages to computing curvatures within a series of larger neighbourhood analysis windows have been demonstrated by authors such as Dikau (1989), Wood (1996), and Smith et al. (2006) (MacMillan and Shary, 2009).

The fundamental geomorphometric variables constitute basic building blocks for deriving combined indices such as the topographic wetness index (TWI) or the topographic position index (TPI) and for performing further and more sophisticated land surface analyses and classifications (Evans and Minar, 2011). The use of geomorphometric field variables to identify landform classes and features dates back over four decades (Wilson, 2012). Over the last twenty years, several methods have been developed to automate the extraction of land surface features from DEMs (e.g Graff and Usery, 1993; Miliaresis and Argialas, 1999; Dymond et al., 1995; Wood, 1996; Schmidt and Hewitt, 2004; Dragut and Blaschke, 2006). Several widely applied approaches to automated classification of land surface elements are based on consideration of local surface shape as measured by slope gradient and signs or values of curvatures (MacMillan and Shary, 2009). The capabilities of this approach are best illustrated by Wood (1996) who used slope, cross-sectional and minimum and maximum profile curvatures calculated within the analysis window to define six categories of surface-specific elements: peaks, ridges, passes, channels, pits, and plains (Hengl and Evans, 2009).

Blaszczynski (1997) proposed an alternative method for curvature calculation and determining whether cells were on convex or concave parts of the land surface. His approach to curvature analysis was used for classifying a continuous landscape surface represented by a DEM into a series of discrete areas representing geomorphometric surface-specific elements or features such as crests, troughs, side slopes, open and enclosed basins, inclined and horizontal flats. Blaszczynski (1997) showed how convexity and concavity can be identified by modifying the calculation of the average percent slope gradient for a centre cell within a kernel. The calculated value of this curvature measure or 'signed average local relief', $R^s_{0,0}$, assigned to the cell in the centre of a $n \times n$ kernel (where n is odd and n >=3) is:

$$R^s_{0,0} = 100 \frac{1}{rN} \sum_i \sum_j \frac{(z_{0,0} - z_{i,j})}{\sqrt{(x_0 - x_j)^2 - (y_0 - y_i)^2}} \qquad (15)$$

where $z_{0,0}$ is the elevation of the cell at the kernel centre (x_0, y_0), the $z_{i,j}$ are the elevation values in the surrounding cells within the kernel at positions $i,j = -(n-1)/2,\ldots,(n-1)/2$ with respect to the kernel centre, r is DEM grid spatial resolution (i.e. cell size), N is the number of surrounding cells within the kernel, and x,y are the spatial coordinates of the cells.

Yokoyama et al. (2002) proposed a geomorphometric variable termed 'openness' which is related to local curvature. Openness is directly related to land surface line-of-sight and thus is derived taking the maximum angle of vision from a point on the land surface within a given maximum radial distance. The calculated value at each cell of a DEM is:

$$\phi_{0,0} = 90 - \beta_{0,0} = 90 - \frac{1}{N_D} \sum_d^{N_D} \max_{i,j=1,2,\ldots,L} \left\{ \arctan\left(\frac{z_{0,0} - z^d_{i,j}}{r\sqrt{(x_0 - x^d_j)^2 - (y_0 - y^d_i)^2}} \right) \right\} \qquad (16)$$

where $\phi_{0,0}$, $\beta_{0,0}$ and $z_{0,0}$ are the (positive) openness, the maximum elevation angle and the elevation of the cell at the kernel centre (x_0, y_0), respectively, the $z^d_{i,j}$ are the elevation values in the cells located on a profile along an azimuth $d \in D=\{0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o\}$ and within the kernel at positions $i,j = -(n-1)/2,\ldots,(n-1)/2$ with respect to the kernel centre, N_D is the number of azimuths or compass directions (8 in the original algorithm), L is kernel (half) size, r is DEM grid spatial resolution, and x,y are the spatial coordinates of the cells. Similarly, a negative openness was defined using the minimum elevation angle.

2.1 Software for digital land surface analysis

The analysis of DEMs was traditionally conducted using stand-alone programs developed for scientific use such as MicroDEM (Guth et al., 1987), TAPES-G (Gallant and Wilson, 1996), TARDEM (Tarboton, 1997), and TauDEM (Tarboton and Ames, 2001). Whilst some stand-alone programs made links with GIS to take advantage of their superior facilities for viewing, panning and management of DEMs, others relied on image processing software. LandSerf (Wood, 1998, 2009b) for example was a comprehensive, multi-platform suite of programs for multi-scale land surface analysis and visualisation, aimed at researchers and written in Java. It computed a variety of land surface variables from a DEM (slope, aspect, profile, plan, longitudinal and cross-sectional curvature), enabling a variety of land surface features (channels, ridges, peaks, passes, pits and plains) to be classified.

While specialised software such as Landserf will continue to be used by researchers where comprehensiveness of functionality is paramount, we identify a broader range of application areas in which users value the convenience of carrying out preparatory data processing with the same software they will use for further analysis and presentation of results. GIS software is now so widely adopted by many scientific professionals, for whom land surface analysis is just one necessary step towards a final result and the overhead of investing time to learn specialised software for geomorphometry may not be justified. These users create a demand for more comprehensive and accessible functionality for land surface analysis in mainstream GIS software. Gessler et al. (2009) have recognised the scarcity of user-friendly and computationally efficient GIS tools as the most serious bottleneck in semi-automated geomorphometric mapping.

Most GIS now include functions for computing the most common geomorphometric operations on DEMs such as the maximum down-slope gradient, slope aspect, convexity, and direction of down-gradient flow paths (Gallant and Wilson, 2000). However, in most GIS, only the simpler algorithms are often used and implemented using only a 3×3 kernel. With many users typically working with only one DEM product, land surface variables computed using windows of such limited dimension will detect only variations in topography at one scale determined by the DEM resolution (Gallant and Wilson, 2000). Dragut and Eisank (2011) have argued that the capability for multi-scale extraction of landscape features is still lacking and may be hindering studies of how landform elements are extracted and recognised from continuous fields of elevation data.

There have been some previous attempts of providing ArcGIS toolboxes for geomorphometric analysis. Currently, to the best knowledge of the authors, two toolboxes are publicly available: the ArcGIS Geomorphometry Toolbox (Reuter, 2009) and the ArcGIS Geomorphometry and Gradient Metrics Toolbox (Evans et al., 2014). The ArcGIS Geomorphometry Toolbox is a comprehensive ArcGIS toolbox containing a large number of geomorphometric algorithms. Current toolbox version 1.0.6 is only compatible with ArcGIS version 10.0 (ArcGIS version to be retired in 2015; Esri, 2015). The toolbox is provided as a commercial software program (it is almost free for pure research) (Reuter, 2009). The toolbox includes a large number of geomorphometric functions. The geomorphometric functions provided are grouped under menus labelled: "*Landforms*", and "*Terrain parameters*". "*Landforms*" menu includes eleven algorithms for land surface classification (Pennock et al., 1994; MacMillan and Pettapiece, 1997; MacMillan et al., 2000; Meybeck et al., 2001; Park et al., 2001; Weiss, 2001; Reuter, 2004; Dobos et al., 2005; Iwahashi and Pike, 2007) and derivation of some combined indices (Bolstad's et al. (1998) Landform Index, Weiss' (2001) TPI). "*Terrain parameters*" menu includes several algorithms for the calculation of fundamental geomorphometric variables such as slope, aspect, curvature (profile, plan, tangential), stream order, and watershed area (MacMillan et al., 2000; Reuter, 2004; Esri, 2010), and of alternative variables such as openness (Yokoyama et al., 2002), and some combined indices such as TWI, TPI, mass balance index (Moller et al., 2008), and elevation residuals (Wilson and Gallant, 2000). Fundamental field variables (e.g. slope gradient, aspect, curvature) are calculated through a fixed neighbourhood operation by moving a 3×3 window across a DEM utilising ArcGIS functions (Esri, 2010). Curvature can also be calculated using two alternative formulae (not documented or referenced). Some combined indices (e.g. TWI, TPI, elevation residuals) can be calculated using a range of windows extents by utilising ArcGIS focal statistics functions (e.g. focal mean). The openness variable, requiring direct access to neighbour elevation values within the analysis window, can be obtained up to a window extent of 9×9 (Reuter, 2009). A basic description or reference (embedded in source code) of the algorithms provided is included. Separated documentation or toolbox help pages are not provided.

The ArcGIS Geomorphometry and Gradient Metrics Toolbox (Evans et al., 2014) is an ArcGIS toolbox containing various utilities and geomorphometric algorithms. Current toolbox version 2.0 is compatible with ArcGIS versions 10.x and is provided as open source (freeware). The toolbox is devised to support ecological modelling and hence functions provided are grouped under menus labelled "*Directionality*", "*Statistics*", "*Texture and Configuration*", and "*Temperature and Moisture*". The first two menus include general purpose utilities and statistical functions (e.g. correlation). "*Texture and Configuration*" menu includes functions for the calculation of indices such as dissection (Evans, 1972), hierarchical slope position (Murphy et al., 2010), surface curvature index (Bolstad and Lillesand, 1992), roughness (i.e. local elevation variance), slope position (Gallant and Wilson, 2000), and surface relief ratio (Pike, 1971). "*Temperature and Moisture*" menu include functions for the calculation of indices such as compound topographic index (Moore et al., 1993), heat load index (McCune and Keon, 2002), integrated moisture index (Iverson et al., 1997), and site exposure index (Balice et al., 2000). Indices are calculated combining standard ArcGIS functions (working through a fixed 3×3 window) such as slope gradient, aspect, and curvature (Esri, 2014) with ArcGIS focal statistics functions operating at a range of windows extents. A basic description (embedded in source code) of the tools is included. A "Read Me.pdf" file including a description and references of the algorithms is provided. Toolbox help pages are not provided. Both toolboxes above require the ArcGIS Spatial Analyst extension to operate.

This brief review has considered a variety of software packages for conducting geomorphometry and identified various user requirements that are not fully met by existing software. A more comprehensive review of software for geomorphometry by Wood (2009a) in which eight packages (ArcGIS Workstation, GRASS, ILWIS, LandSerf, MicroDEM, RiverTools, SAGA and TAS) were assessed for their geomorphometric capabilities concluded there is considerable scope for software that fills the gap that still exists between comprehensive, specialist tools and the limited functionality presently implemented by major GIS vendors.

Using Wood's (2009a) triangular diagram of the software landscape for geomorphometry, we are proposing a solution that fills the gap between the standalone tools and a standard install of a mainstream GIS (Fig. 1). The tool takes advantage of the power of the GIS to handle the large DEM sizes, whilst retaining ease of navigation through its custom user interface to a more sophisticated set of methods, including support for multi-scale analysis of DEMs.

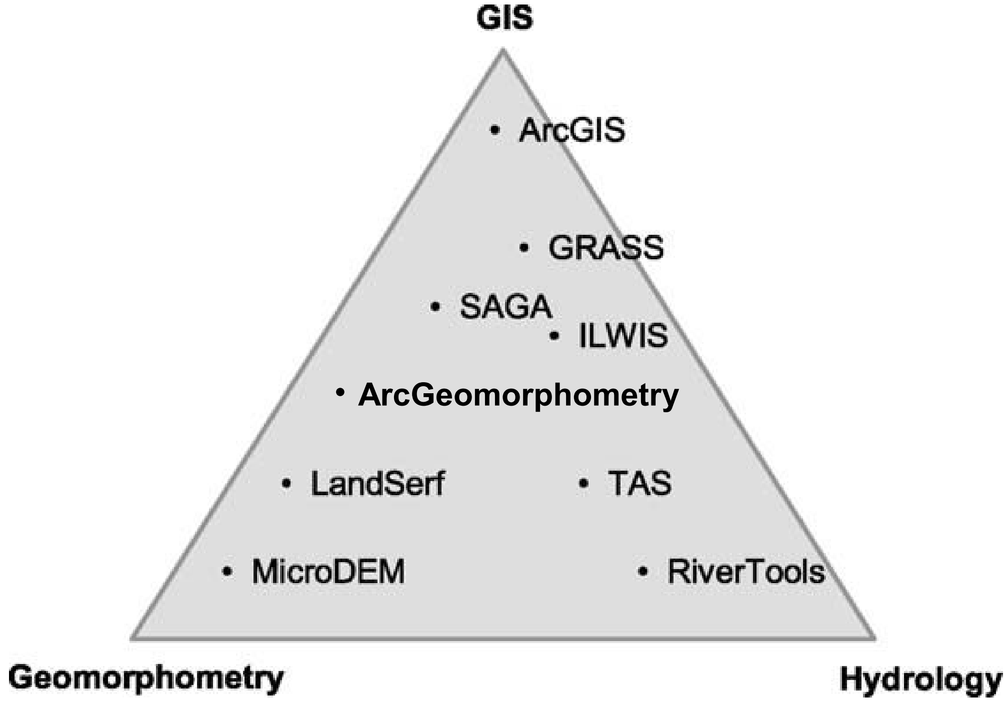


Fig. 1. Positioning of the new tool within the existing software landscape for geomorphometry (modified from Wood, 2009a).

The next section describes the development environment and the functions implemented to create a more comprehensive and accessible tool set for conducting geomorphometry efficiently and productively in ArcGIS.

3. ArcGeomorphometry toolbox for ArcGIS

3.1 The ArcGIS development environment

According to recent reports, the Esri ArcGIS software is the most commonly used GIS worldwide (GITA, 2008; Daratech Inc., 2011). Esri's flagship product, ArcGIS for Desktop, is widely used in education, industry and several scientific research fields, especially in the geosciences. In many of these fields, there is a need to conduct geomorphometric analysis. ArcGIS for Desktop includes the Spatial Analyst extension that can be used for this purpose. While Spatial Analyst provides efficient methods for constructing DEMs from various source data formats, its explicit functions for geomorphometric analysis are limited and implemented using a fixed 3×3 kernel (e.g. slope gradient, aspect, and curvature based on the method described by Zevenbergen and Thorne, 1987).

ArcGIS supports several popular programming and scripting languages, although Esri has officially embraced Python as the recommended programming language for working with ArcGIS (Zandbergen, 2012; Esri, 2014). User created Python scripts can be integrated into ArcGIS as script tools, which work just like standard ArcGIS processing (geoprocessing) tools and can be accessed from the ArcGIS user interface. Python Toolboxes are geoprocessing toolboxes created entirely in Python and the tools contained within, look, act, and work just like the Toolboxes and tools created in any other way. This allows easy sharing of tools among users and researchers and facilitates amendments and addition of new tools to the toolbox.

ArcGIS geoprocessing functionality is accessible through Python using ArcPy library. Of particular importance to this study, Numerical Python (NumPy) is a numerical library for scientific computing, including support for powerful N-dimensional array objects.

The ability to construct more complex functionality from the basic language syntax, the widespread availability of the scripting language and the many types of DEM data already available in ArcGIS raster data format led to the decision to develop the extended functionality for geomorphometric analysis using the ArcGIS Python environment. This new functionality was then made accessible to the user using a Python Toolbox, which can be installed, shared and modified. By following the conventions for Python Toolboxes design (Esri, 2014), the code for the GUI integrates with the standard ArcToolbox with the result that, once loaded, ArcGeomorphometry menus, dialogues, help pages, etc., appear seamlessly incorporated within ArcGIS.

3.2 . The ArcGeomorphometry tools

The ArcGeomorphometry tools allow landscapes stored as DEMs in any ArcGIS raster format to be analysed and classified and land surface features to be identified at different spatial scales. Standard menus and dialogue boxes guide the user through a series of steps required to produce a geomorphometric analysis or land surface classification, without having to program these procedures (Rigol-Sanchez and Stuart, 2005). Users can conduct a series of classifications of a DEM into different land surface features (i.e. surface-specific elements) and by quickly reviewing the results, can progressively refine the classifications. ArcGeomorphometry focus on field local variables and implements many of the commonly needed functions for geomorphometric analysis of DEMs (Table 1). It currently provides functions for true multi-scale land surface analysis and classification based on the methods proposed by Evans (1972, 1979, 1980) and Wood (1996); Shary (1995) and Shary et al., (2002); Blaszczynski (1997); and Yokoyama et al. (2002). These functions are grouped by method under menus labelled "*Evans-Wood Method*"; "*Shary Method*"; "*Average Relief*"; and "*Openness*" respectively. The algorithms provided under *Evans-Wood* and *Shary* menus make use of Numpy functions to fit a bivariate quadratic polynomial (for each DEM cell) to elevation values contained within the given window/kernel size extent by least squares. Polynomial parameters are then used to obtain geomorphometric variables. The algorithms under *Average Relief* and *Openness* make use of Numpy array indexing capabilities.

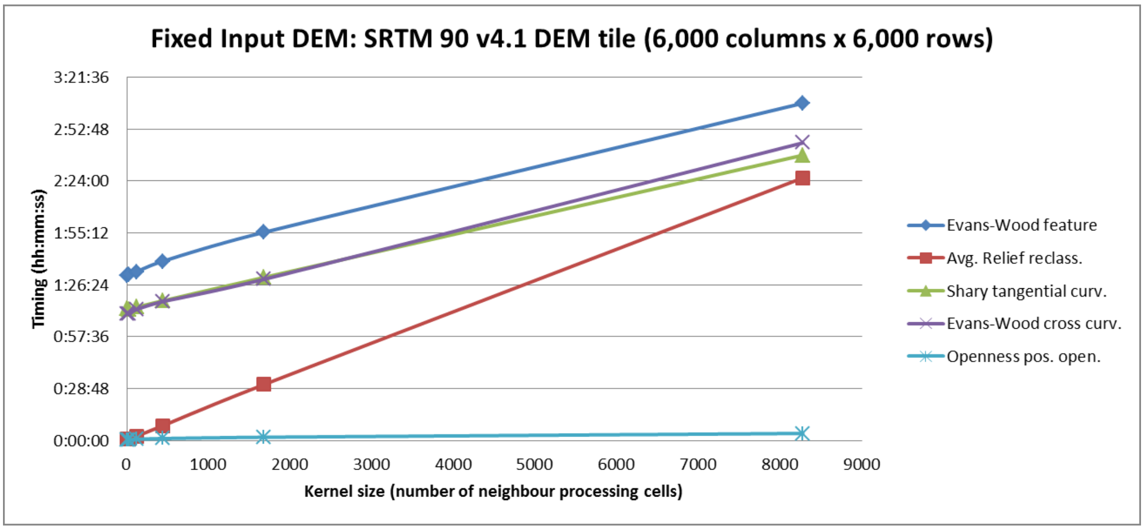
Table 1

Functions of ArcGeomorphometry.

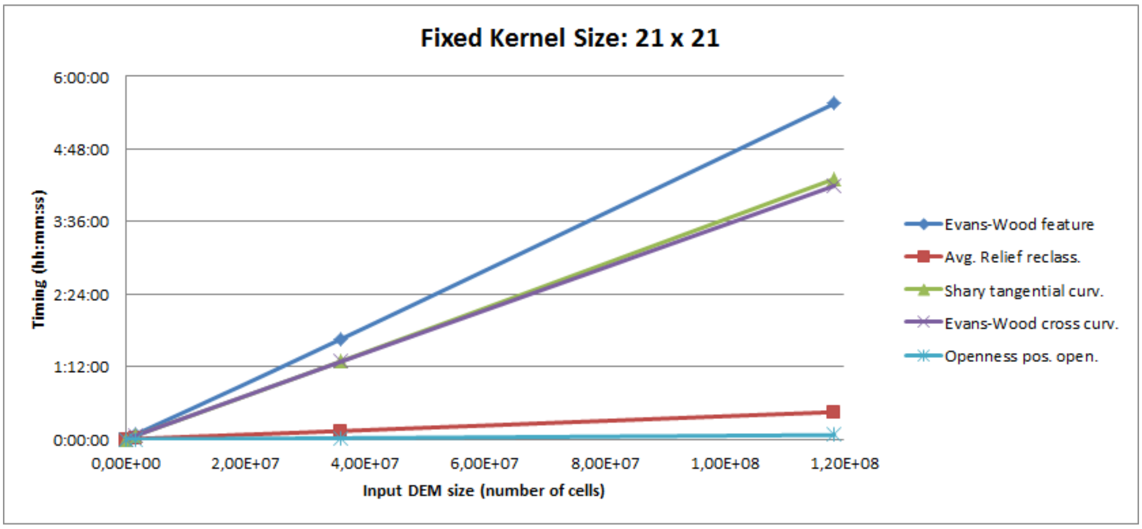
Function name	Description
Average Relief functions	
average slope	Calculate average slope percent
classified average relief	Reclassify signed average local relief grid using user defined slope and signed average local relief cut-offs
signed average relief	Calculate signed average local relief
Openness functions	
negative openness	Calculate 8-direction average minimum elevation angle below surface
positive openness	Calculate 8-direction average maximum elevation angle above surface
Evans-Wood Method functions	
aspect	Compute slope orientation or aspect
elevationSmoothed	Return elevation smoothed by quadratic function
crossCurvature	Compute cross-sectional curvature
feature	Classify DEM into surface-specific elements (pit, peak, ridge, channel, pass, plane) using user-defined slope and curvature thresholds
longCurvature	Compute longitudinal curvature
maxProfCurvature	Compute maximum profile curvature

minProfCurvature	Compute minimum profile curvature
modified Evans-Young	Modified Evans-Young algorithm (pre-filtering)
planCurvature	Compute plan curvature
profileCurvature	Compute profile curvature
Slope	Compute slope steepness
Shary Method functions	
aspect	Compute slope orientation or aspect
crossCurvature	Compute cross-profile curvature
longCurvature	Compute longitudinal curvature
maxProfCurvature	Compute maximum profile curvature
meanCurvature	Compute mean curvature
minProfCurvature	Compute minimum profile curvature
planCurvature	Compute plan curvature
profileCurvature	Compute profile curvature
rotor	Compute rotor
tangentialCurvature	Compute tangential curvature
totalCurvature	Compute total curvature
totalGaussianCurvature	Compute total Gaussian curvature
totalRingCurvature	Compute total ring curvature
slope	Compute slope steepness
unsphericity	Compute unsphericity

The toolbox runs on any computer running ArcGIS for Desktop 10.1 SP1 or higher. It consists of a Python script that realise the analysis routines, user menu, dialogue boxes and basic help. Additional help pages are stored as xml files. Installed tools can also be run in a standalone mode by calling them from a Python window or ModelBuilder, but are intended primarily to be operated through a graphical menu. Tools use linear map units, such as feet or meters, and consequently, it is assumed that input DEM has a projected coordinate system. The maximum size of the input raster DEM, i.e. maximum number of cells, is limited by available RAM on computer up to a maximum RAM allocation per Python 32-bit process imposed by the operating system (2GB). In practice, DEMs of 1.0E+08 cells can be processed in a standard personal computer (4GB RAM, Core i3-2100 processor running at 3.10GHz) in periods from few minutes to several hours depending on the function and kernel size selected (Fig. 2). As indicated above, DEM analyses involving direct operations on neighbour cells values such as cell sum, subtraction or multiplication can be efficiently performed in Numpy in one step using array indexing. This is the case for functions under *Average Relief* and *Openness*. DEM analyses based on more complex operations that require simultaneous access to all neighbouring cell values within the kernel such as function fitting procedures (e.g. *Evans-Wood Method* or *Shary Method*) have to be undertaken in two steps (neighbour data load using array indexing; and kernel operation, e.g. function fitting by least squares, solving a system of linear scalar equations for each DEM cell). Typically, Numpy array views are used to access neighbouring cell values.



(a)



(b)

Fig. 2. Timings for some ArcGeomorphometry functions: (a) Computed using an input DEM of 6,000 columns by 6,000 rows (3.60E+07 cells) and increasing kernel sizes (3×3, 5×5, 11×11, 21×21, 41×41, 91×91). (b) Computed using a kernel size of 21×21 and increasing input DEM sizes (276 columns × 173 rows, 1,702×903, 6,000×6,000, 10,880 x 10,880). Processing was performed using a standard personal computer (4GB RAM, Core i3-2100 processor running at 3.10GHz).

The ArcGeomorphometry toolbox allows the user to perform multi-scale geomorphometric analyses. Hence, in all cases once the input DEM is selected, the size of the processing kernel (or analysis window) for land surface analysis is selected by typing in the desired square dimension (a circle diameter for openness). Any positive odd kernel size is allowed, so that maximum size of analysis window is limited only by the spatial dimensions of input DEM or available system resources.

The results of each land surface classification are graphically displayed if the tool is executed from within ArcGIS ArcMap or ArcScene applications. Thus the user can readily display further ArcGIS grids (such as gridded land cover data or a previous geomorphological mapping of an area) and overlay vector data sets such as contour lines on top of output grids (Fig. 3). Adding this contextual information facilitates an immediate visual assessment of results, which can highlight incongruities or give credence to elements of a landscape classification.

4. The operation of ArcGeomorphometry illustrated using an example DEM

Fig. 3(a) shows a sample DEM used to illustrate the operation of the ArcGeomorphometry Toolbox. The data are included on the ArcGIS for Desktop installation media. The DEM covers an area of 23.64km by 23.04km of the town of Stowe, Vermont, USA, with a cell size of 30m by 30m (788 columns × 768 rows). The topography of the area corresponds to a moderately rugged mountainous terrain. The maximum elevation value (1,319m) is located close to the upper-left corner of the area (Green Mountains) and minimum value (134m) is located close to the lower border at the bottom of the main valley (Little River).

Fig. 3 illustrates the processing of the DEM with ArcGeomorphometry *Average Relief* tools using a range of kernel sizes. Once the input DEM is selected, the size of the analysis window for land surface analysis is selected by typing in the desired square dimension. Any positive odd kernel size is allowed, although 81×81 cells has been found practically to be sufficient to extract many amplitudes of land surface features from DEMs with ground resolutions in the range from 10-200m. 81 cells equate to a 2.4km × 2.4km search window for a 30m DEM and for this terrain produce a very smoothed output surface. Figs. 3(b) to (f) are graphical displays generated within ArcGIS ArcMap. The spatial pattern of land surface features identified by the methods is generally consistent with what would be interpreted from topographic mapping of the area. When the classification is repeated using larger kernel sizes, the number and the complexity of the land surface features identified is reduced and greater smoothing of the land surface occurs.

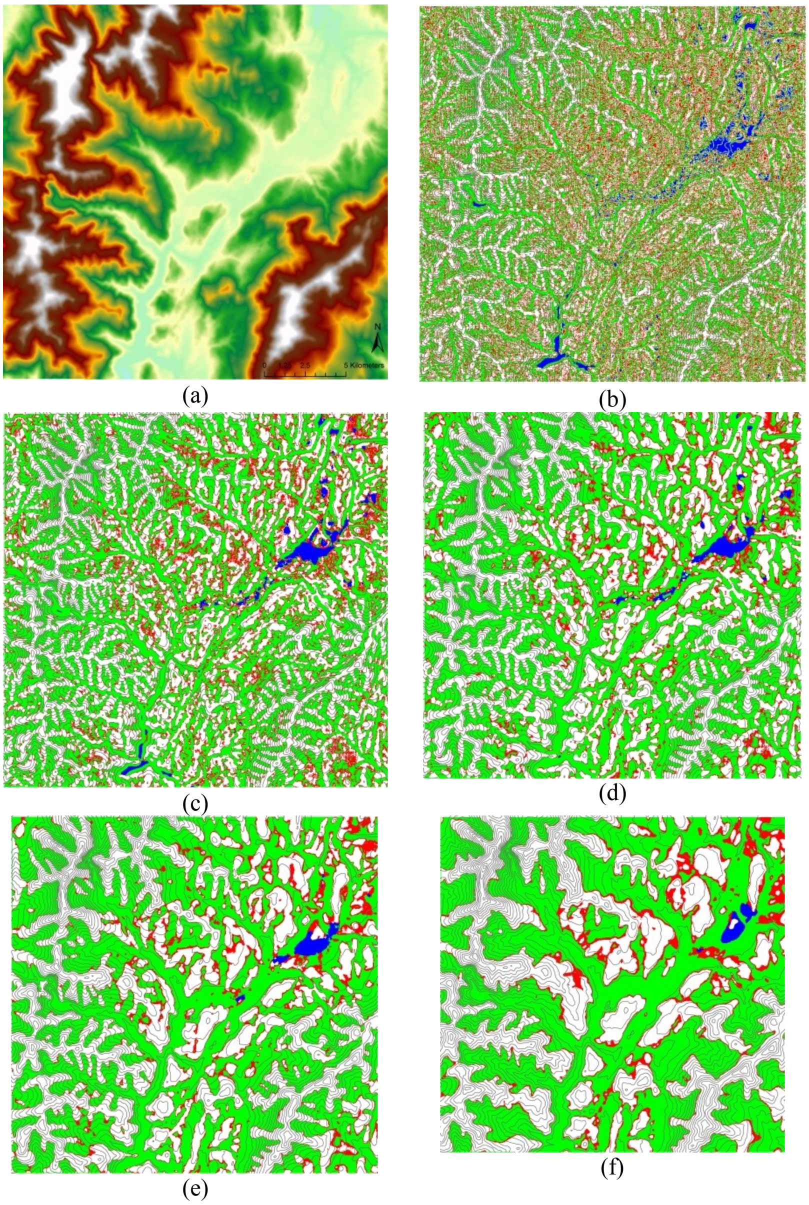


Fig. 3. Test DEM (a) and results of classification using ArcGeomorphometry *Average Relief* tool computed using a: (b) 3×3 kernel (90m×90m). (c) 11×11 kernel (330m×330m). (d) 21×21 kernel (630m×630m). (e) 41×41 kernel (1,230m×1,230m). (f) 81×81 kernel (2,430m×2,430m). Maps of classifications are overlain with a vector layer of contour lines at 50m interval. Note that the extent of the area that can be classified by the processing without edge effects is reduced as the kernel size increases.

The sequence of classified grids in Fig. 3(b) – (f) illustrate that, as expected, land surface features extracted by using large kernel sizes have comparably larger spatial dimensions than those identified by small kernel sizes. Land surface features classified by large kernels reflect the variations of topography at a broader scale, corresponding roughly to features whose dimensions are similar to the length of entire hillsides. It can also be seen that the classification using the "standard" 3×3 kernel produces an image with less coherence and a higher local variance from which it is more difficult to interpret land surface features. In this example using a 30m resolution DEM, the range of kernel sizes from 3×3 to 81×81 covers a range of landscape features from the micro-scale (0-30m) to the meso-scale (30-2,430m) (Dikau, 1989). Indicative timings for performing the above classifications are shown in Fig. 2. Fig. 4 shows four other results as perspective views of the processing of the sample DEM using different functions of the toolbox generated within ArcGIS ArcScene.

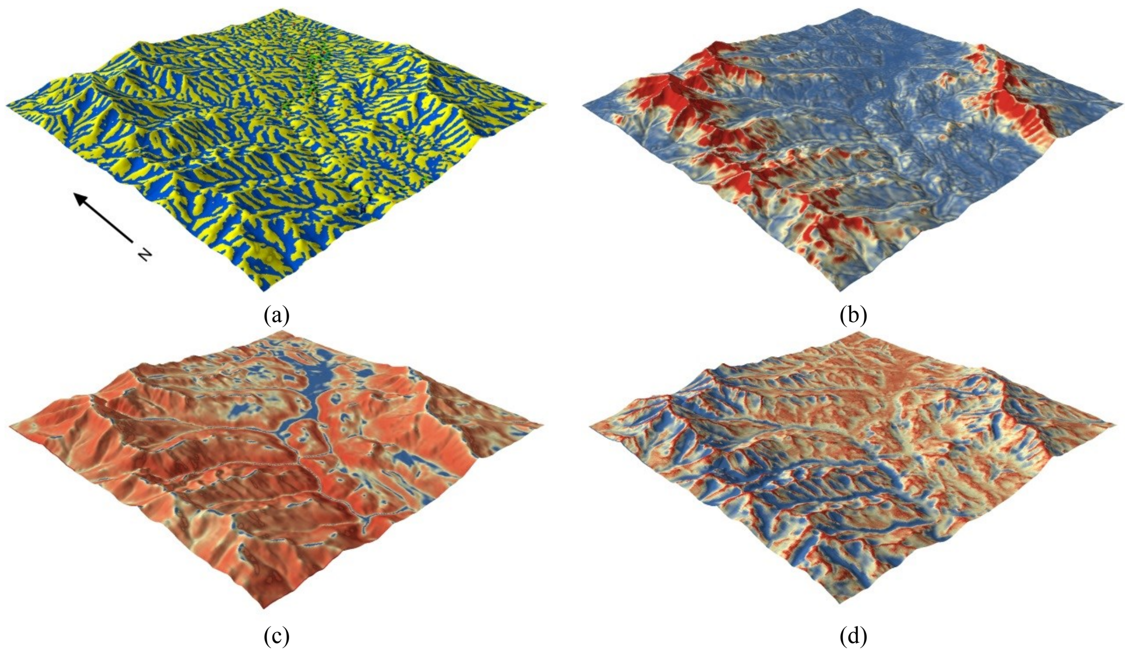


Fig. 4. 2.5D perspective views illustrating processing of test DEM using ArcGeomorphometry tools. (a) *Evans-Wood Method* "*feature*" classification calculated using a 11×11 kernel (330m×330m). (b) *Shary Method* "*unsphericity*" variable calculated using a 11×11 kernel. (c) *Shary Method* "*plan curvature*" variable calculated using a 21×21 kernel (630m×630m). (d) *Openness* "*positive openness*" variable calculated using a 31×31 kernel (930m×930m). Vertical scale is exaggerated by a factor of 1.5.

5. Conclusions and planned enhancements

The ArcGeomorphometry toolbox provides a means for conducting exploratory, iterative and multi-scale land surface analysis with DEMs in the ArcGIS environment. Operating through the graphical user interface, users can easily and flexibly select the desired function from a comprehensive selection and vary the size of the kernel to identify features from the land surface model at different scales. Parameter values can be adjusted flexibly to enable analysis and classification of different land surface elements on the basis of both curvature and degree of slope of the surface at various scales. Because the results from each iteration are immediately available for detailed inspection using the sophisticated visualisation techniques of GIS, users may browse, zoom, query, reclassify and overlay additional data sets to determine when an acceptable classification has been found. The results are produced in a format that can be immediately interpreted, integrated with additional data, or analysed further using any available ArcGIS functions. The toolbox are highly portable and functions can also be used within ArcGIS ModelBuilder or other scripts, in both interactive and batch processing modes.

If a reference data set exists, for example if a field survey has previously produced geomorphological mapping for a given locality, the ArcGeomorphometry tools can be used to determine kernel and threshold parameter values that classify a DEM for this area into land surface units that conform with the mapping. Once these parameters have been established, it may be possible to apply similar parameter settings to recognise similar landscape features from a DEM of the same specification but covering a more extensive area for which geomorphological mapping has not been previously produced.

A few limitations apply to processing DEMs with the ArcGeomorphometry Toolbox. While the time for the per-pixel algorithms to process a gridded DEM increases quadratically as the DEM extent is increased, for neighbourhood algorithms the time increases at faster rates as the size of the kernel is increased, since many more cells have to be processed in the input layer to create a single value in the output grid. The present tests of ArcGeomorphometry suggested that quite large kernel sizes (e.g. 81×81) may sometimes be required to extract some larger amplitude land surface features. While there is no limitation in the software upon the size of kernel that can be used, working with kernels much larger than those normally available in standard systems leads to 'non-interactive' processing unless the DEM extent is quite small (Fig. 2). The availability of higher resolution DEM products, such as 10m products derived from InSAR data or submetric LIDAR DEM data, while potentially allowing much finer surface detail to be revealed, would lead to much longer processing times if such high spatial resolution data sets were used for extracting features of the same dimensionality and over similar extents as those in this illustration.

In the present version of ArcGeomorphometry, if any cell in the processing kernel has a null value, then the output for the cell at the centre of that kernel will be null. As a consequence, each edge of the classified DEM created by the processing will be reduced by one-half of the kernel size, leading to the overall dimensions of the output grid being reduced by the number of (rows=columns=k) in the kernel.

Future improvements envisaged for the toolbox include: (a) The storage of DEMs as binary files on disk to circumvent the limit of input DEM size imposed by the operating system. (b) To allow the user to constrain analyses to specific quadrants of the analysis kernel (e.g. where the resultant cell value is determined only by cells in the north-east or south-west quadrant of the kernel). This may be a simple way to explore directional dependence of some land surface features or the influence of particular orientations upon features on land surface geomorphometry.

Acknowledgments

Comments from two anonymous reviewers greatly helped in improving the manuscript. This work benefited from a “British Council – la Caixa" fellowship and an EU Marie Curie research grant to the Department of Geography, School of GeoSciences at the University of Edinburgh, UK. This study was supported by Research Group RNM-189 and the project CADESEM P11-RNM-8115 of the of the Junta de Andalucia Regional Government, Spain.

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