

Creating Mountains out of Mole Hills: Automatic Identification of Hills and Ranges Using Morphometric Analysis

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Abstract

This paper examines the relationship between scale of observation and landform features and their representation in map form. The research is premised on the idea that large scale features are defined by the smaller features that comprise them (that mountain ranges are a collection of clustered yet individually identifiable mountains or hills). In preference to subjective selection of the higher order features, we propose a methodology for automatically discerning mountain ranges as well as the smaller hills that constitute them. A mountainous region can be defined by its prominence (relative height among surrounding features) and various morphological characteristics including the variability in morphology. The algorithm presented here uses derivatives of elevation and the density of morphological properties in order to automatically identify individual hills or mountains and ranges together with their extents. Being able to create generalised views of landscape morphology is considered to be part of the model generalisation process and is an essential prerequisite to spatial query and to the cartographic portrayal of these features at a range of scales (levels of detail). For the purposes of evaluation the algorithm was applied to the hills around Edinburgh city and the hills and ranges around Fort William, Scotland. The research reflects on the challenge of defining the subjective nature of what is a 'hill' or a 'mountain', but reminds us that a map seeks to capture the essence and characteristic form of the landscape – something that is necessarily fuzzy and scale dependent.

Keywords: Morphology, landscape visualisation, morphological paronomies, model generalisation

1. Introduction

The shape of the earth's surface reflects a complex interplay between anthropogenic and physical processes – a set of systems and processes operating at a range of spatial and temporal scales. The form of that shape has a huge bearing on patterns of habitation, and land use. Typically we wish to view that surface at multiple levels of detail (or scale) in order to study the scale invariance of processes, their scale dependency (Wood, 1999), the relationship between complexity and scale, for example Andrieu (1996), or to characterise scales at which surface behaviour changes substantially (Mark & Aronson, 1984). We wish to be able to view and characterise a landscape at both the fine scale – exploring morphographic elements (Evans, 1990), through to the distributional patterns of landforms (such as glacial or volcanic landforms) – at the level of 'atlas cartography' where the emphasis is on morphostructural regions (rather than individually identifiable landforms) (Evans 1990). In other words we need multi scale mapping that supports different scales of landform analysis (Summerfield, 2005). Our cartographic representations also need to support the correct interpretation and 'reading' of the landscape in support of navigational tasks or safe route planning (Purves *et al.*, 2002). The breadth of cartographic techniques developed over the centuries for representing the earth's morphology is testament to its importance in these and many other tasks (Imhof, 1982).

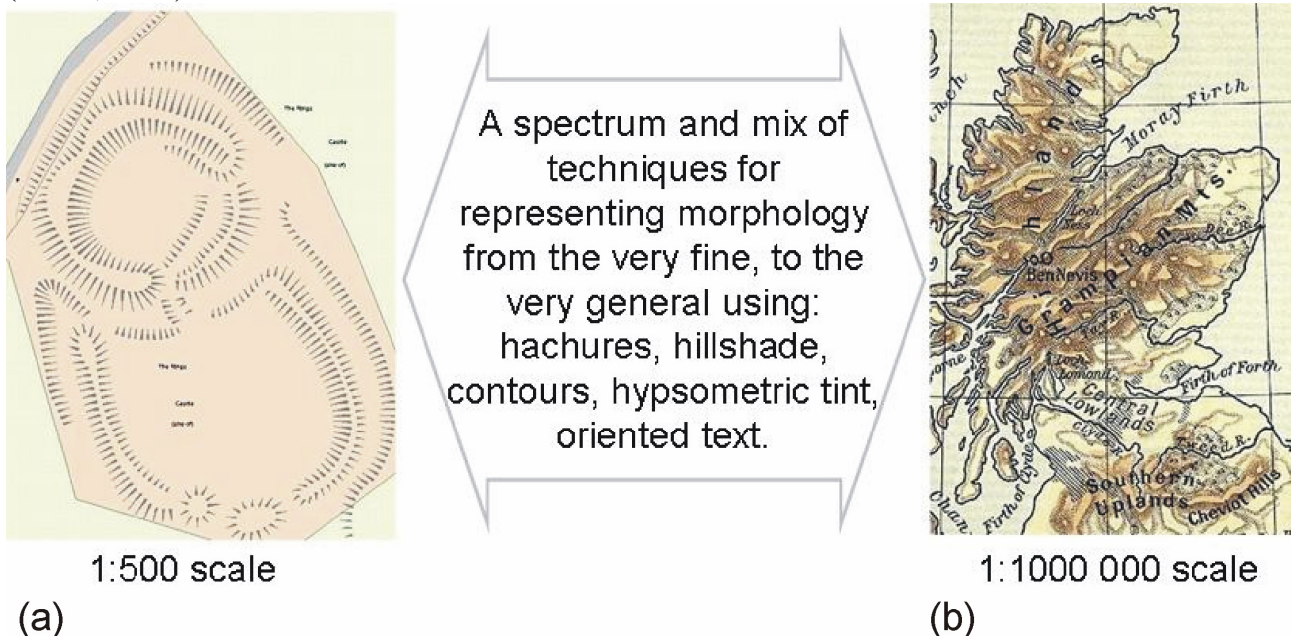


Figure 1: A continuum of techniques to convey morphographic elements and morphostructural regions (Figure 1a: Regnauld *et al* 2002; Figure 1b: Shepherd, 1926).

At the very fine scale we might use hachuring (Regnauld *et al.*, 2002), hill shading and/or contours to represent morphology (Mackanness & Stevens, 2006). At the course scale we might use colour tints, and at a synoptic level we can use text to convey highly generalised caricatures of components of the earth's surface. Though we use this range of visualisations techniques to support effective interpretation of relief at different levels of detail (Figure 1), they all point to the same underlying morphological features – from the individual hills, to the connected set of ridges, and from the collection of hills, to ranges and mountains chains. At the fine scale we will discern the relationship between fluvial processes or surficial geology and morphology, but only at a scale of 1:2,000,000 can we separate out the Paris basin, the Alps, the Massif Central and the Pyrenees (Figure 2).



Figure 2: The Paris basin is upper centre, the Alps lower right, the volcanic region of the Massif Central lower centre and the Pyrenees middle bottom. (Source: Nasa imagery)

To minimise redundancy, to facilitate update, and multi scale analysis, we envisage a single detailed database capable of supporting multiple scale representations that would enable representation of the earth's morphology at various levels of detail, and thereby supporting ideas of intelligent zoom (Frank & Timpf, 1994) and spatial query appropriate to a given level of detail. This idea is reflected in the concept of multiple representation databases (Sarjakoski, 2007) that enable us to 1) have a single point of database update, 2) define in a consistent way how generalised morphologies are produced, and 3) support non-visual spatial queries. By creating bounded extents we can support creation of alternate forms of visualisation (Figure 1) such as automatic labelling of mountain ranges. Furthermore by enriching the database (through the creation of paronomic relationships between individual hills and these regions) (Chaudhry & Mackaness, 2006) we can answer questions such as: 'Does Ben Macdui lie in the Grampians?' But before we can offer such solutions, we need a methodology that enables us to link morphographic elements to morphostructural regions. This paper presents an approach for the automatic identification of landforms and their extents. Section 2.0 describes the methodology and section 3.0 considers its application and evaluation in a number of case studies.

2. Methodology: Hills and Ranges

In this research we are interested in automatically detecting boundaries or extents of hills and ranges. The degree to which we can precisely define the boundary of a geographic object varies enormously (Burrough & Frank, 1996; Campari, 1996). This observation is reflected in research on the modelling of fuzzy boundaries (Clementini & Felice, 1996; Cohn & Gotts, 1996). Nevertheless the boundary that separates the entity from its environment is one of the marks of its individuality (Casati *et al.*, 1998). Some boundaries are general in their form, and it is appropriate to represent those boundaries at a small scale (such as the extent of a wetland, or a mountainous region) whilst other boundaries can only meaningfully be conveyed at the large scale (such as a conveying the detail in a property boundary). A systematic treatment of boundaries has been attempted by Smith (1995), who argued that boundaries can be divided into two basic types: bona-fide boundaries and fiat-boundaries (Smith & Varzi, 1997; Smith & Varzi, 2000). A boundary that is 'bona fide' is one that is a 'thing in itself' and exists even in the absence of all delineating or conceptualising activity (river-banks or coastlines are examples of bona fide boundaries). In that sense they are boundaries which exist independently of all human cognitive acts and 'are a matter of qualitative differentiations or discontinuities in the underlying reality' (Smith 1995, p476). The other type of boundary is a 'fiat' boundary in which the boundary owes its existence to acts of human decision or

decree, in some way related to human cognitive phenomena. Thus ‘fiat boundaries are boundaries which exist only in virtue of the different sorts of demarcations effected cognitively by human beings’ (Smith 1995, p476). These are delineations which correspond to no genuine heterogeneity on the side of the bounded entities themselves. Examples would include political borders, property-lines, urban settlement, hill and range boundaries. This paper focuses on derivation of the fiat boundaries of hills and ranges.

The methodology is built around the idea that where there are a collection of prominences that have sufficient distinction from adjoining landforms, are of sufficient density, frequency and extent then they are considered differentiable from other regions (other ranges, or other morphostructural features such as deltas or plateaus). In essence the analysis of the morphology at the fine scale enables us to create ‘containers’ that define the extent of a range or mountain region, and from this create a set of ‘parent child’ relations by which we can define the partonomic membership of each hill within a region. Many attempts have been made to mathematically define (and thus automatically identify) different types of features in the landscape. What constitutes a hill, a mountain chain or region is a very scale dependent issue. The person asking the question may have a very vague prototypical view of a particular region (Kuhn, 2001) and that view will alter depending on the context. There again, someone may have a precise mathematical definition that, in the context of a spatial query returns a definitive answer. Many researchers have arrived at different definitions of what a mountain or hill is (Bonsall, 1974; Campbell, 1992; Cohen, 1979; Purchase, 1997) – the definitions often reflecting localised understandings of the landscape (for example, that the notion of a mountain in Scotland is very different when viewed in a Himalayan context). One example of an attempt to define the mountains of Scotland is reflected in the ‘Munros’ of Scotland, named after Sir Munro who compiled and published in 1891 a list of all mountains over 3000 feet in Scotland (he identified 277 separate mountains). He did not define how prominent the mountain should be, only that there be ‘sufficient separation’ from neighbouring tops (www.smc.org.uk). The subjective definition of what constitutes a Munro is reflected in revision to the list in 1995 resulting in something that was defined as a ‘Murdo’ (Scottish hills at least 3000 feet in height with a drop of at least 30 metres on all sides) of which there are 444 (Dawson, 1995).

At its simplest we might use absolute height to define a hill or a mountain. But caricature (important to cartography and our conceptual grouping of things) has much to do with observable difference and being able to sufficiently differentiate between mountains in the landscape. For example each of us has a conceptual understanding of plateau, delta or mountain and our labelling of these features reflects a shared agreement and understanding. Prominence (the amount by which a hill rises above the local area) clearly influences people’s perception of whether something deserves the epithet ‘hill’. Additionally its morphological variability as compared with its surroundings is also a critical factor (Fisher & Wood, 1998). The morphological variability can be measured in terms of the frequency of peaks, passes and ridges, and additionally in terms of its pits, channels and planes (Fisher *et al.*, 2004). These descriptors are useful in modelling variability and can thus help characterise a region. The methodology proposed here reflects two essential ingredients: *prominence* and *morphological variance*. These were derived from a generalised digital terrain model (DTM), and combined to create bounded regions that demarcated the individual hills and extent of the range. This provided a basis by which the ‘parent child’ relationships between hills and ranges could be partonomically defined. The end result is a morphologically nested description of the region (Figure 3) which acts as a framework for model generalisation and spatial query. In the following sections we will present different stages of the approach in more detail.

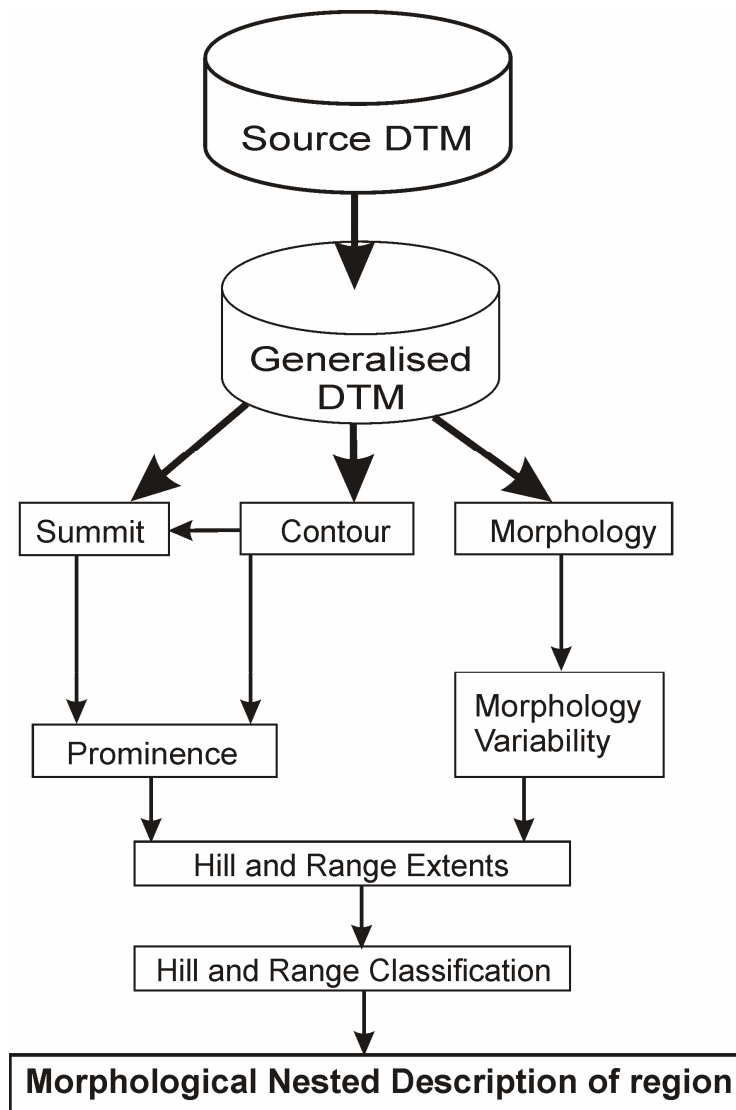


Figure 3: The overall method by which hills and ranges are identified

2.1 Calculating the prominence of a hill

In topography, prominence, may be referred to in terms of relative height, shoulder drop (in America) or prime factor (in Europe), or simply relief (Press & Siever, 1982; Summerfield, 1991) and is a measure of the independent stature of a summit. There are different methods for calculating prominence on a contour map. Here it is defined as the elevation difference between the summit and the lowest closed contour that encircles that summit and with no summit(s) of higher elevation than itself (reflecting the idea of elevation difference with respect to the surroundings). This lowest contour that encircles the summit and no higher summit is called the *key contour* of the summit. To be sure that we identify the correct key contour we must consider an extended area of the DTM that includes the continent that the summit resides within. For a summit such a Ben Nevis (the highest in Great Britain) that extent should in theory incorporate the entire DTM of Great Britain. But this becomes too intensive computationally. Instead it is appropriate to choose a “sufficiently” large extent such that the region of interest lies well within that extent. By way of an example, a “sufficient” extent for Ben Nevis might be a centred square 50km by 25km whilst for the Pyrenees that extent might be a rectangle of 600km by 300km. The point is that the results for any given region are meaningful within the outermost contour that is “closed” within the selected extent. Once the key contour for each summit has been identified, prominence is then calculated as the elevation difference between the elevation of the key contour and the elevation of the summit.

The prominence for each summit was calculated by firstly creating contours from the source digital terrain model (DTM). Ordnance Survey's Land-Form PROFILE[®] dataset was used, which has a resolution of 10m. The contours created (using ArcGIS) from the source DTM were found not to be appropriate for processing because 'spikes' were present around the edges of some contours and some contours were attached to other contours or were broken (Figure 4a and 4b). To avoid these problems, the input DTM was filtered using a smoothing algorithm (Wood, 1996b). The algorithm works by fitting a quadratic polynomial with a given kernel size. The kernel size for the polynomial was empirically determined and was set to 25 cells (25*25). The resultant DTM and contours (interval of 5m) are shown in Figure 5a and 5b.

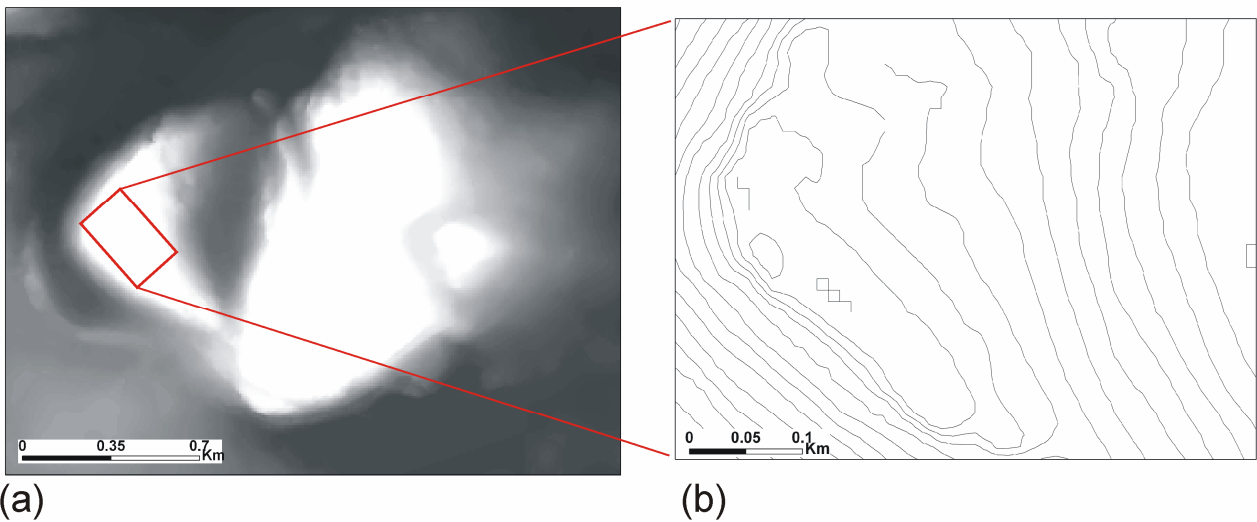


Figure 4: (a) Source DTM (b) 5m Contours derived from the source DTM (note that some contours have 'spikes' and are broken in certain places)

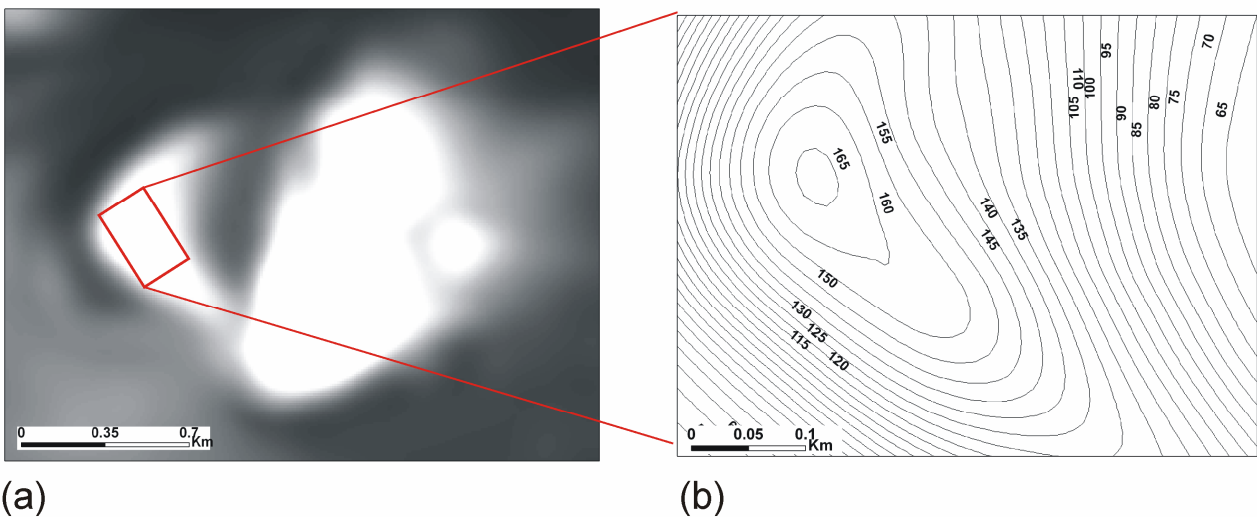


Figure 5: (a) Smoothed DTM; (b) Resultant contours at 5m interval together with height labels

The resultant contours from the generalised DTM were used by the algorithm to identify the summit points and their prominence. The summit points were identified using the highest contours (contours that contain no other contour) and finding the cell from the DTM that has the maximum elevation within each of these contours. For such cells a summit point is generated that stores the location and its elevation (Figure 6). The second step is the calculation of prominence for each summit point. The algorithm finds the key contour for each summit point using the above definition of key contour. It then calculates the prominence by subtracting the summit's elevation from the elevation of the key contour (Figure 6 and Figure 7).

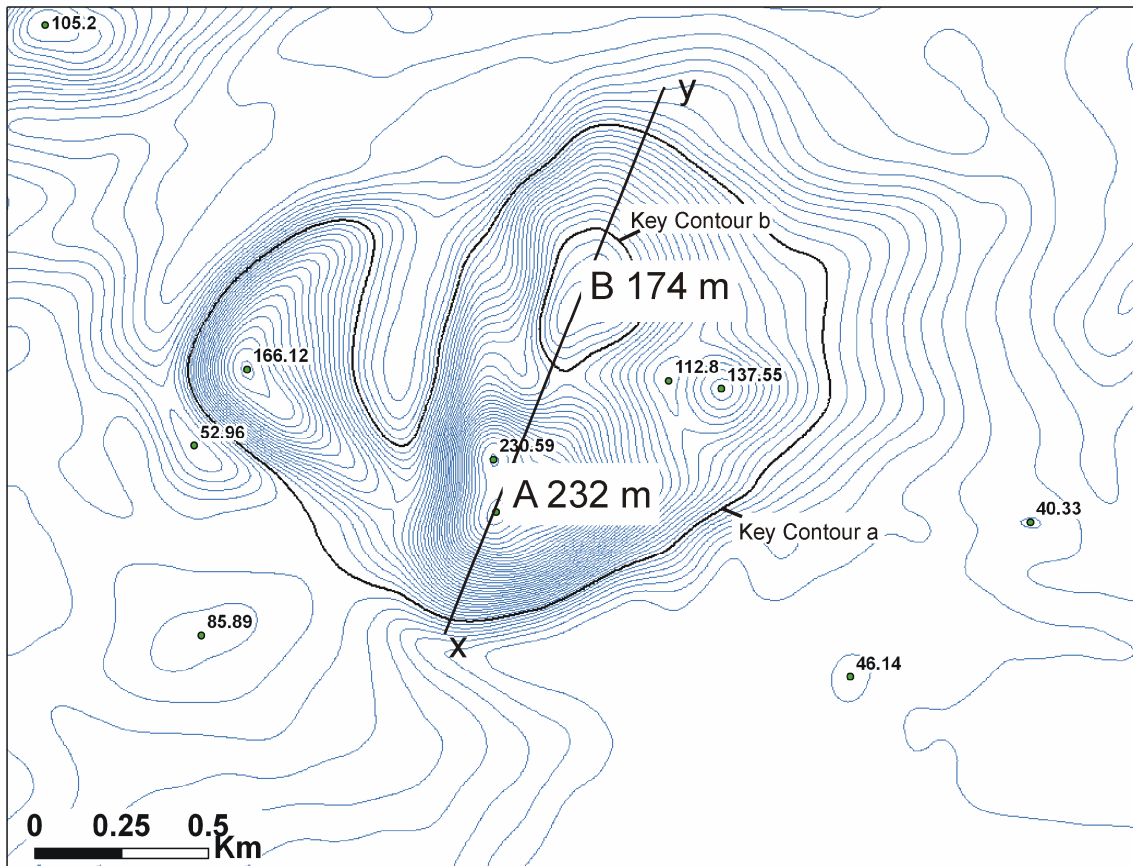


Figure 6: Contours created from a smooth DTM (Figure 5a). Summit points along with their elevation values are shown within each of the highest contours. Key contours of summit A and Peak B are highlighted in bold. Note that all the summit points that are inside the key contour 'a' of summit A are of a lower elevation than summit A (232m)

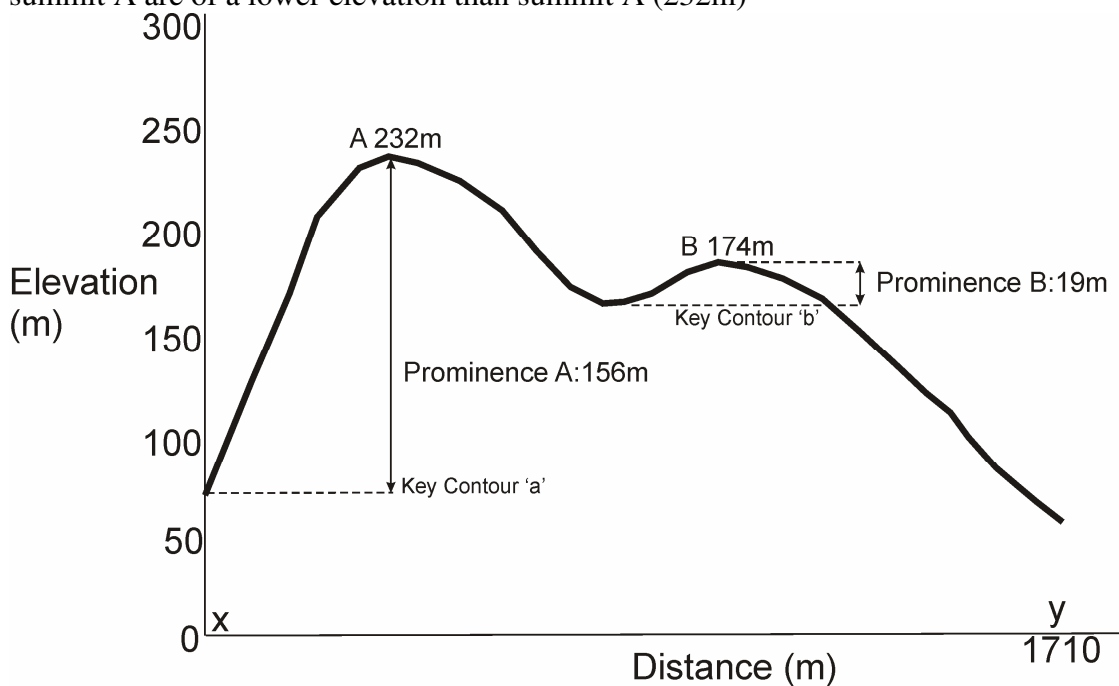


Figure 7: Profile of the transect from Figure 6 showing the Prominence of summits A and B

2.2 Modelling morphological variance

To determine the areal extent of a hill or a mountain's summit along with its prominence we also need to take into account the surface variability between the summit and the key contour. This is

because it is not meaningful to define extent purely in terms of the key contour. Theoretically such a rule would make the coastline of Great Britain the key contour of its highest peak (Ben Nevis at 1344m). This does not accord with our own perception of the extent of the region that contains this peak because the surface between the summit and this key contour is not changing sufficiently. Thus in addition to prominence we also need to model the amount of change in the surface in order to identify the extent of a hill, or mountain range.

This change in elevation of a surface can be modelled based on its morphology. One approach is to classify the surface in terms of its morphometric features or classes (pits, peaks, passes, ridges, channels and planes). Several methods exist for the identification of these morphometric features (Evans, 1972; Maxwell, 1870; Peucker & Douglas, 1974; Tang, 1992). Here we have used a technique developed by Wood (1996a) that uses an approach based on the quadratic approximation of a local window or kernel of given size, in order to find the first (slope) and second derivative (curvature) of the DTM. This method assigns each location of the generalised DTM to one of the six morphometric classes. Due to the scale dependent nature of the phenomena there is a degree of fuzziness in a location's classification (Fisher *et al.*, 2004; Wood, 1996b). This means that a location classified as a peak at one scale may viewed as a ridge at another scale, or a plane at some other scale. There has been a lot of research dealing with modelling the fuzziness of a landform (Fisher, 2000; Robinson, 1988, 2003; Robinson *et al.*, 1988; Uery, 1996; Wood, 1998). In this research the fuzziness in classification was modelled by using the method developed by Wood (1996a, 1996b), whereby the DTM is modelled at different scales using different kernel sizes (3*3 to 51*51). Each location at each kernel size is classified into one of the six morphometric classes. The final class of each location in the resultant surface is the one which is most dominant over all kernels (Figure 8).

The resultant morphometric units or features shown in Figure 8 are converted into polygons. All polygons that are non plane (i.e pit, channel, pass, ridge or peak) depict areas with change in morphology. These polygons are called morphologically variable polygons (Figure 9) and are used by the algorithm to identify the extent of each summit (explained further in the next section).

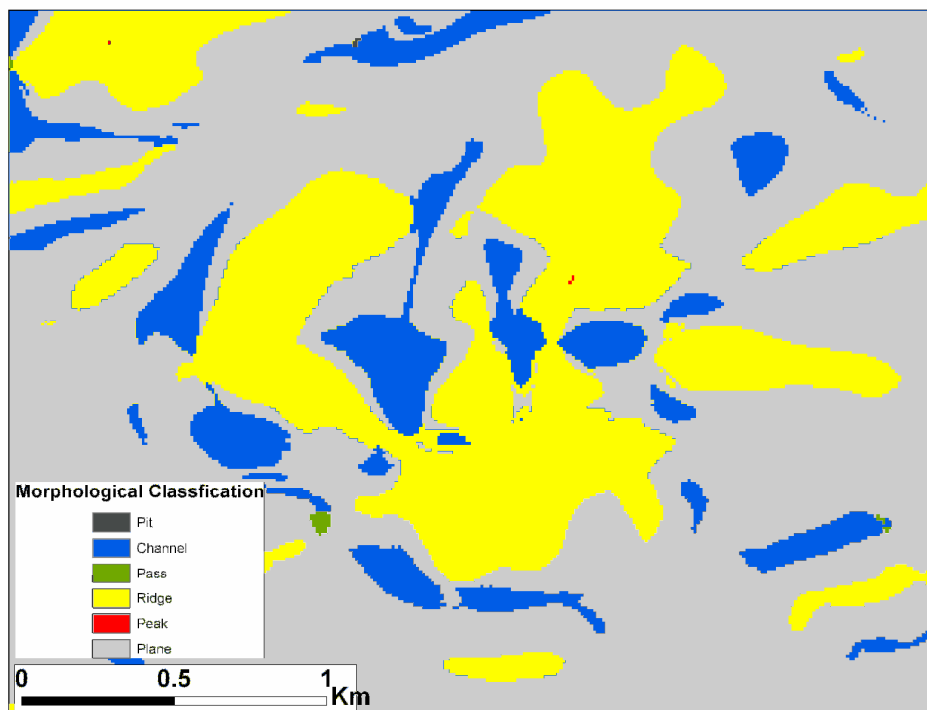


Figure 8: Multiscale morphometric classification of the DTM in Figure 6a. The kernel used ranged from 3*3 to 51*51

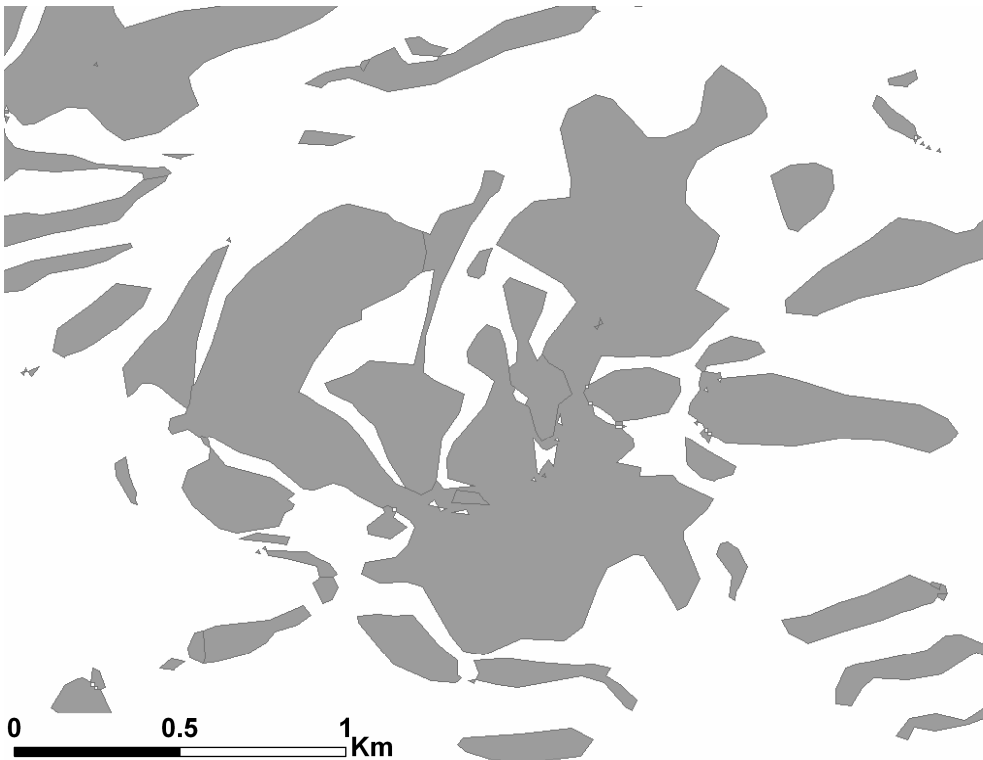


Figure 9: Morphologically variable polygons of the morphometric features shown in Figure 8

2.3 Calculating the extent of hills and ranges

We can now combine the information of prominence, the key contours and the morphologically variable polygons in order to identify the extent of each summit. In essence we identify the contour that best overlaps with the morphologically variable polygons. We start with the key contour polygon of a summit and intersect it with each morphologically variable polygon and calculate the area intersection. The total area intersection divided by the area of the contour polygon gives the percentage of variability within that contour. The percentage is compared against a threshold called the minimum morphology change threshold (MMC). If the percentage is below this threshold it indicates that the surface has low variability and so the next highest contour of the given summit is selected. This process is repeated until the percentage is above or equal to the MMC. The value of MMC was determined empirically and was set to 65%. The value of MMC can be altered according to different applications or intended scales. The contour polygon selected from this process is assigned as the extent of the given summit. This sequence of events is illustrated in Figure 10 in which we start with the key contour for summit A. The percentage of variability is below the MMC (Figure 10a). In Figure 10b and 10c the next higher contour is selected and the same process is repeated and again the percentage is found to be below MMC. In Figure 10d the percentage of variability for summit A is found to be greater than MMC so this contour polygon is assigned as the extent of summit A (Figure 10d). Figure 11 illustrates the extents of all summits identified in Figure 10a and Figure 6.

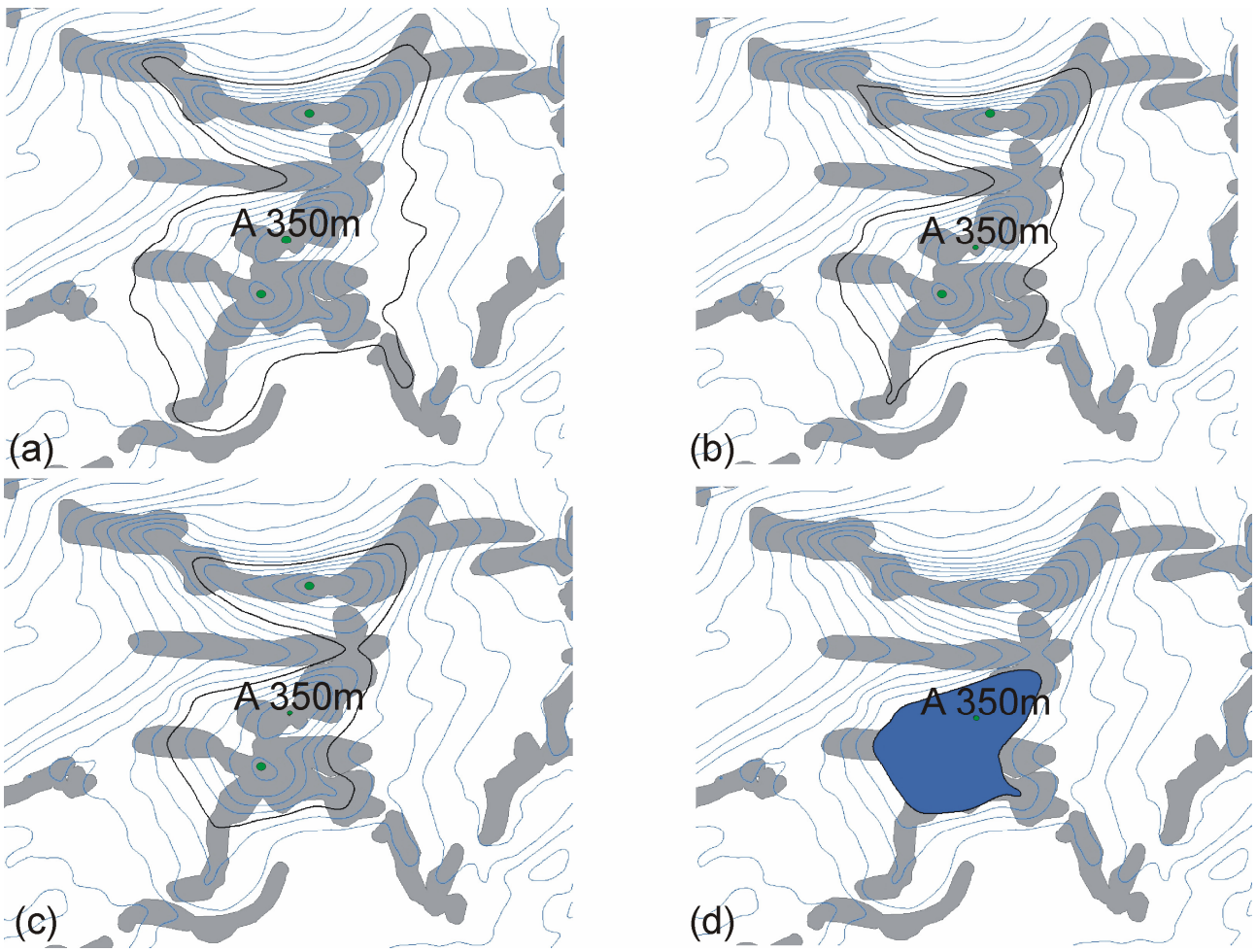


Figure 10: Determining the extent of a summit A. (a): Key contour A, morphologically variable polygons (b) next higher level contour is selected (c) next higher level contour is selected (d) the resultant extent of summit A.

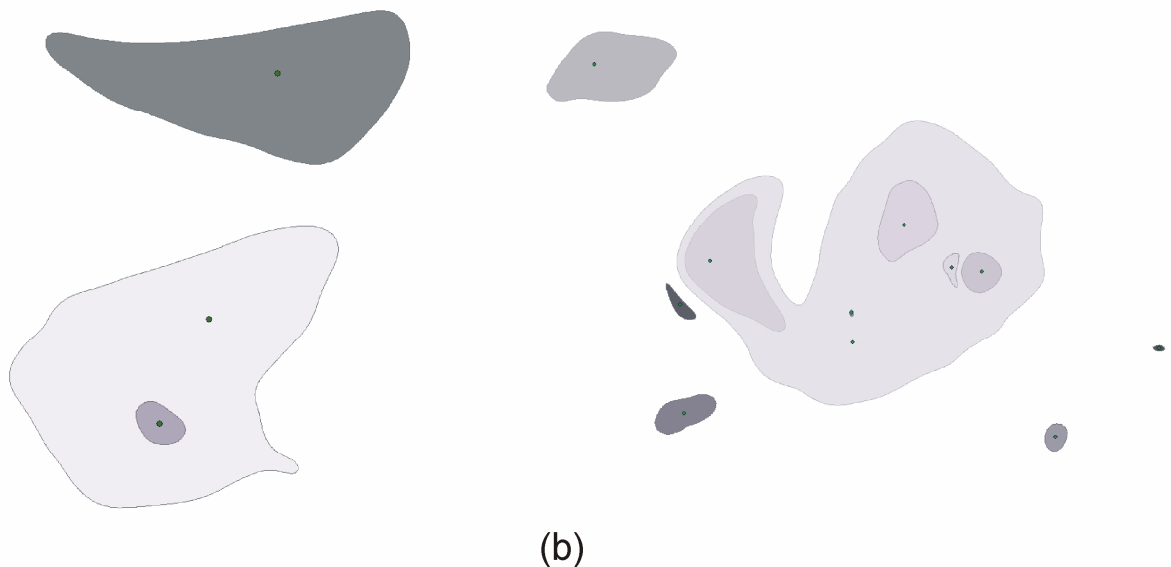


Figure 11: (a) Summits and their extents identified in Figure 10a (b) the summits and extents of Figure 6.

2.4 Modelling 'Parent Child' relationships among groups of hills

One of the most important relationships in terms of spatial objects is parthood relationships. These relationships link parts to a whole (composition) (Varzi, 2007) and provide a means of

creating composite objects at higher levels of abstraction from component objects at high levels of detail, and are thus critical for model generalisation (Molenaar, 1998; van Smaalen, 2003). Once the extents of the summits have been identified we can model the partonomic relationships in terms of parent (whole) and child (part) hills. To identify these child-parent relationships we utilise information relating to the extent of a summit and its key contour. These concepts enable us to group summits on a landmass into a hierarchy showing which summits are ‘sub-peaks’ of others. In this way ranges can be identified from groups of individual hills. If a summit has child summits within its extent then it is a range. On the other hand if a summit doesn’t have any children it can be classified as an isolated hill or a mountain depending upon its prominence and absolute height. There are several definitions for assigning a parent to a hill (Bivouac.com, 2004; Maizlish, 2003). The definition used here is based on *island parentage or encirclement parentage* (Bivouac.com, 2004; Maizlish, 2003). The island parent of a summit is the next highest summit in the prominence line that has a base contour that surrounds the summit, and its key contour is lower than the key contour of the summit in question. Using this definition summit A is the parent of summit B in Figure 6. Similarly in Figure 12 summit A is the parent of summit B and summit C since summit A is the next highest summit and has a contour that surrounds both summit B and summit C (Figure 12).

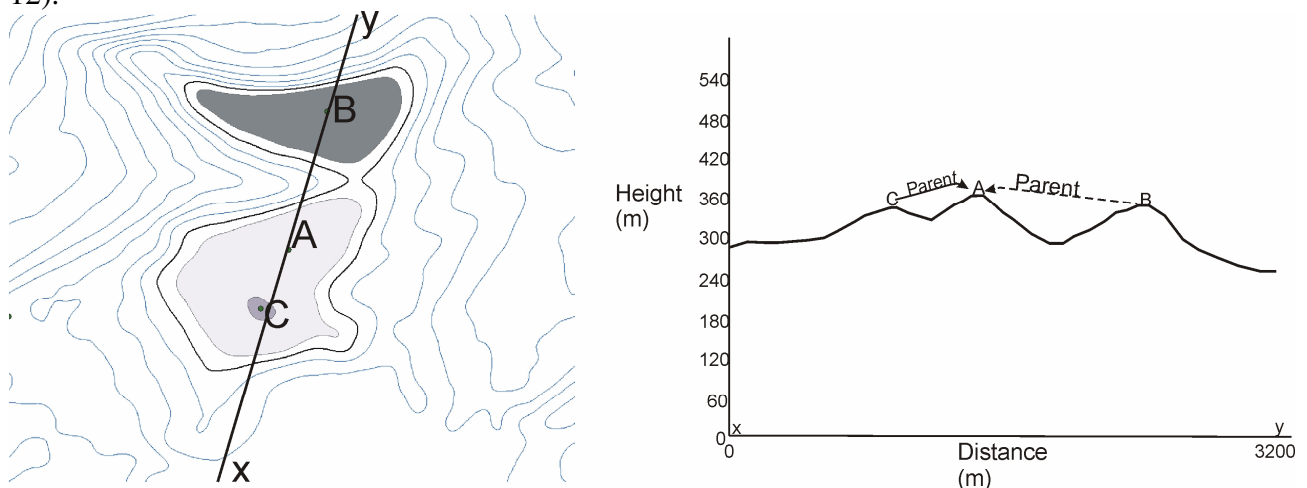


Figure 12: The Parent Child Relationship between summits shown in Figure 10a. Using island parentage definition summit A is the parent of summit B and C. But using the proposed morphological encirclement parentage definition summit A is parent of summit C but not of summit B since the extent of summit A does not cover summit B.

In this research we have limited the extent of a summit in terms of the morphologically variable polygon. We can therefore extend the encirclement parentage definition taking into account the extent of the summit. So for a parent summit in addition to the above mentioned properties its extent also needs to contain the child summit. We call this the *morphological encirclement parentage*. Following this definition in Figure 12 summit A will not be the parent of summit B since the extent of summit A does not cover summit B. By this definition a summit might not have any parent, (ie it may not fall within the extent of its parent summit). In these cases it is either an individual hill (it has no children) or it is an isolated range if it has a set of child summits.

Once the parent child relationship has been identified we can use this relationship along with the value of prominence in order to select only those summits that are significant for the intended database’s level of detail. For instance Figure 13 was created (utilising the results from Figure 11b) by selecting all summits that had a prominence greater than or equal to 35m. Those summits that had a prominence less than 35m were either aggregated into their parent, or if the summit did not have a parent, it was simply deleted. In this way model generalisation can take place such that higher order objects can be created from component objects. The next section presents a case study of a few regions on which this methodology was subsequently applied.

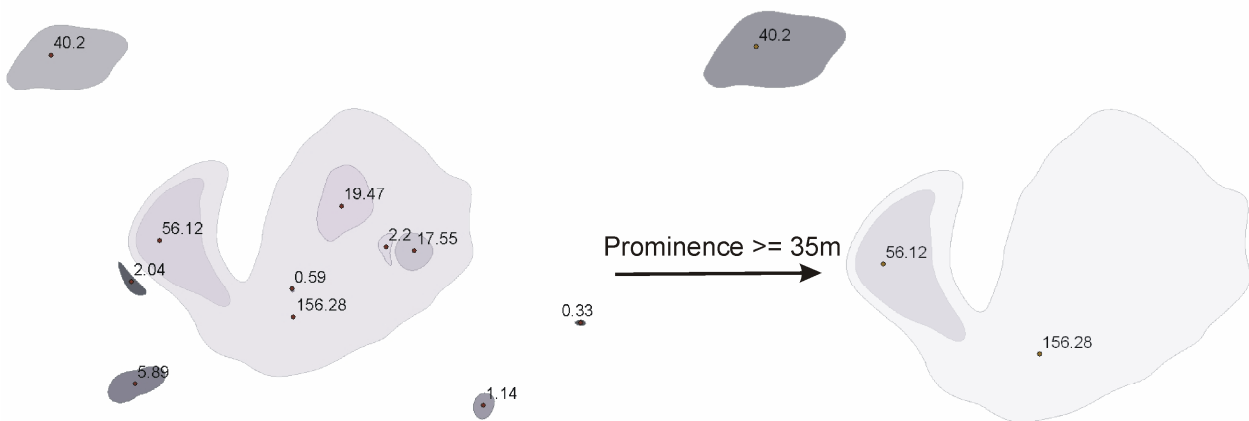


Figure 13: Using a prominence threshold of 35m. The summit B (prominence of 19m), (see Figure 7) has been aggregated into its parent Peak A (prominence 156m).

3. Case Study Illustrations

The algorithm summarised pictorially in Figure 3 and presented in pseudocode below, was implemented in Java, and used functionality from ArcGIS 9.0 and LandSerf (URL: <http://www.soi.city.ac.uk/~jwo/landserf/landserf220/>). It was applied in the derivation of hills and ranges intended for representation at the small scale (1:250 000) directly from a high resolution DTM (Ordnance Survey Land-Form PROFILE dataset with a 10m resolution).

Summary of the algorithm

1. Smooth the detailed input DTM using Landserf with a kernel size of 25*25
2. Create contours at 5m interval from the smoothed DTM;
3. Create summit points: Within each highest contour (contour that does not contain any other contour) create a (summit) point geometry to store highest elevation within that contour;
4. Calculate the prominence of each summit
 - 4a. For each summit find the key contour i.e. the lowest elevation closed contour that encircles the summit in question and does not contain any other summit higher than the given summit;
 - 4b. Subtract the elevation of the key contour from the elevation of the summit (this is the prominence of the summit);
5. Model the morphology in terms of morphometric classification of the input DTM using Landserf with mult-scale option and a range of kernel sizes from 3*3 to 51*51;
6. Convert the morphometric regions (5) to polygons;
7. Remove all polygons classified as plane regions;
8. Calculate the extent of each summit:
 - 8a. Select the key contour of the given summit
 - 8b. Calculate the total area intersection of this contour with all the interacting morphometric polygons (7).
 - 8c. Calculate the percentage of variability by dividing the total area of 8b by the area of the contour.
 - 8d. If area of stage 8c is less then MMC then select the next higher contour for the given summit and repeat 8b-8d until the area becomes larger than or equal to MMC. This contour is the extent of the summit.
9. Assign parent and child relationships

9a. For a given summit 'A', if the first next highest summit whose key contour 'b' contains summit 'A' and whose extent found from step 8d also contains summit A then this is assigned as the parent of summit 'A'.

3.1 The Pentlands

Figure 14 shows the source DTM for a region south of Edinburgh along with the text points of prominent hills and ranges at 1:250 000 scale selected from Ordnance Survey's product Strategi®. Figure 15 shows hills and ranges that have a prominence of greater than or equal to 35m. Except for Castle law and White Craig, the text points of all other hills and ranges fall within their extents. Note that some hill and range boundaries do not have any text points associated with them. The likely cartographic reasons for this are discussed in section 4.0.

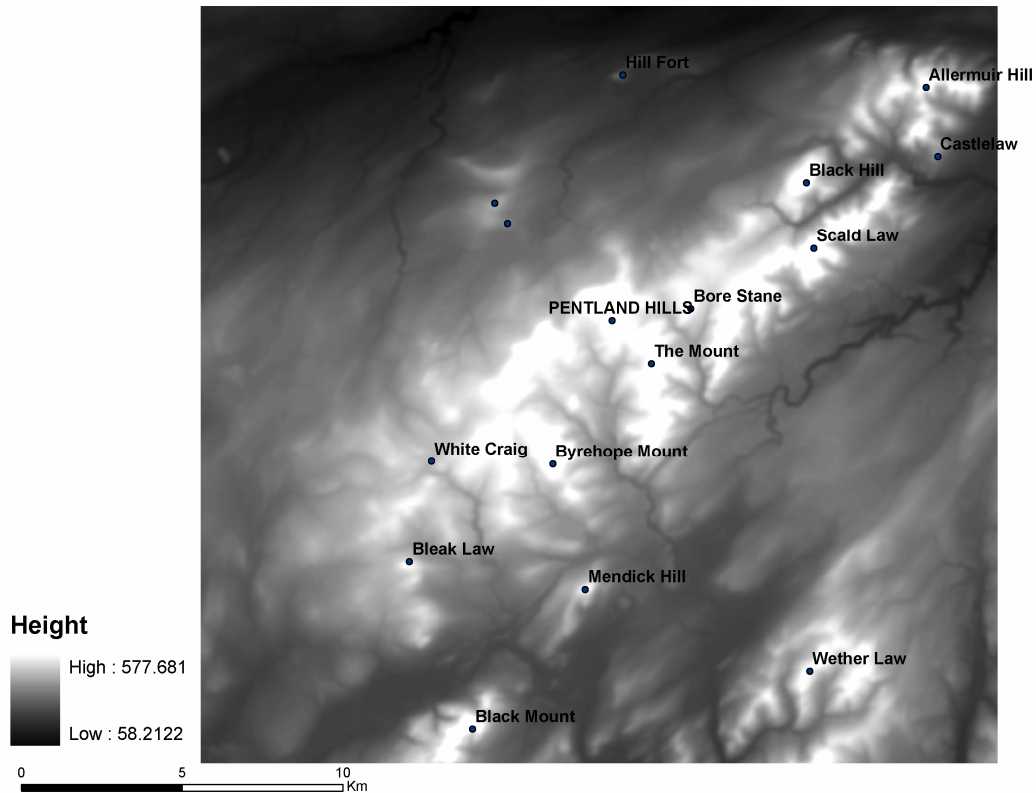


Figure 14: DTM (Land-Form PROFILE) south of Edinburgh. The text points are from Strategi (Ordnance Survey © Crown Copyright. All rights reserved).

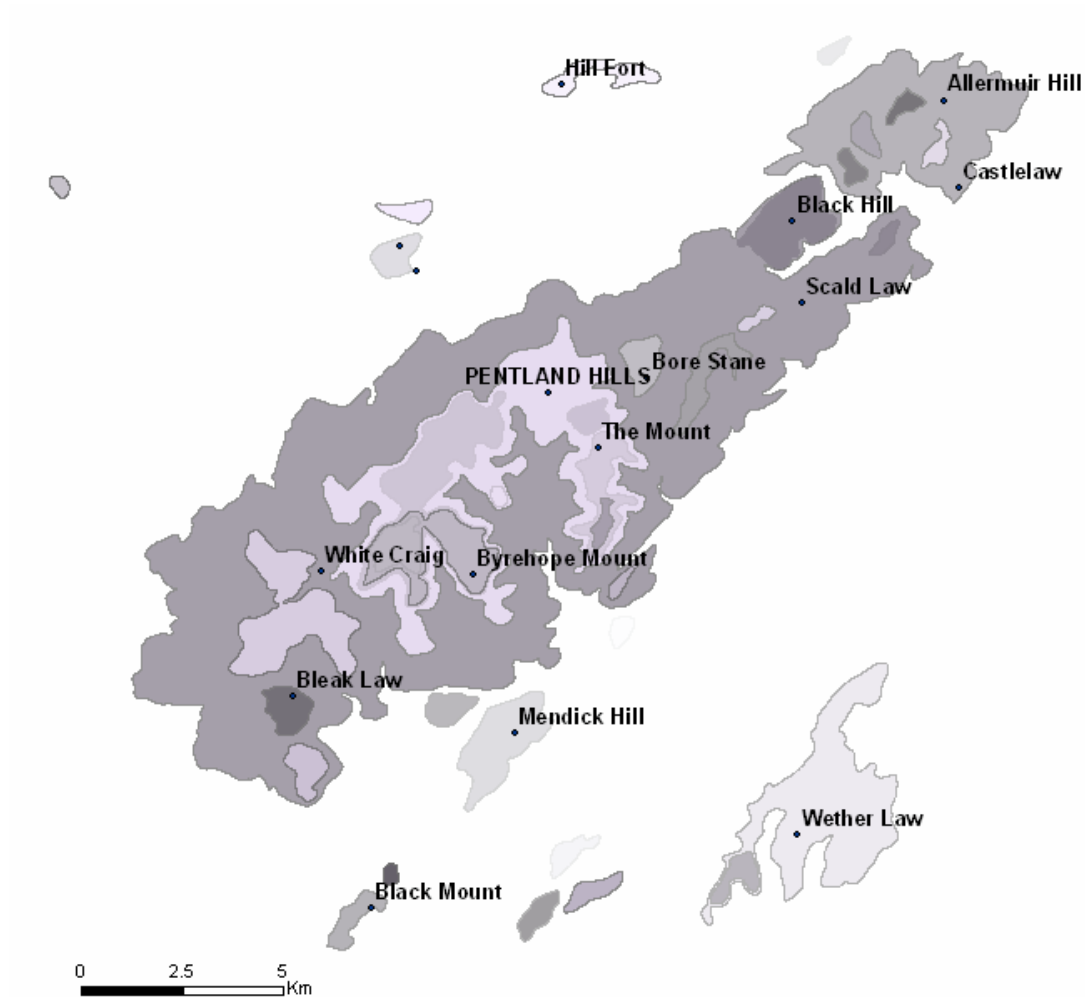


Figure 15: Resultant hills and range extents (prominence above or equal to 35m) along with text points selected from Strategi.

3.2 Region around Fort William

A second test area selected was the region around Fort William, Scotland. The input DTM for this area along with prominent text points selected from Strategi are shown in Figure 16. This region contains three major mountain ranges, Ben Nevis range, Ben Alder range and Mamore range (Figure 17). Ben Nevis Range extends 15km eastwards of Fort William (Williams, 2000) and includes mountains such as Carn Mor Dearg, Aonach Beag and Aonach Mor (Figure 18a). The Mamore mountain range is 15km long running between Loch Leven and Glen Nevis and contains mountains such as Stob Ban, Am Bodach, Stob Corie a' Mahil (Figure 18b). The resultant mountains and range extents identified by the algorithm are shown in Figure 17. Because of limited space not all the text points from Strategi representing hills and ranges are included in Figure 16 and 17. Figure 18 shows an inset of a Ben Nevis, Mamore ranges along with the text points associated with these smaller regions.

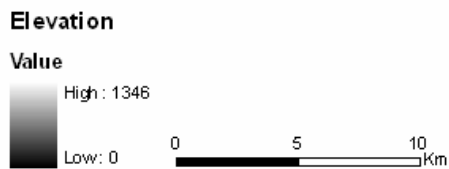
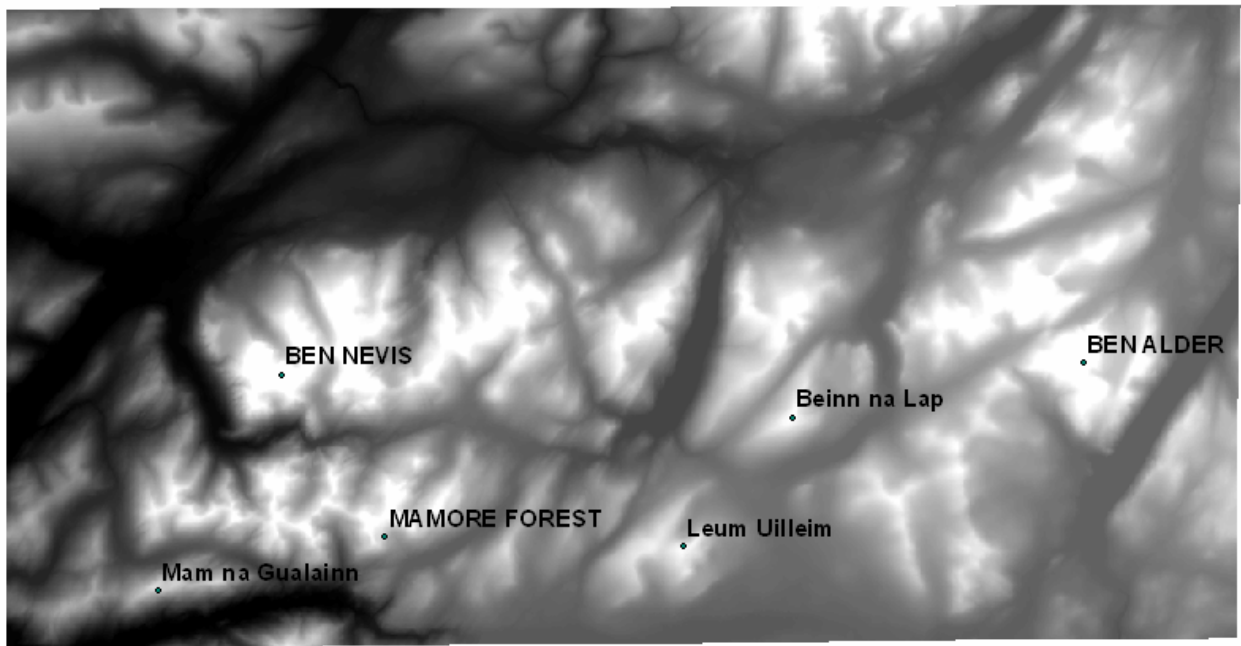


Figure 16: DTM (Land-Form PROFILE) for Fort William (Ordnance Survey © Crown Copyright. All rights reserved).

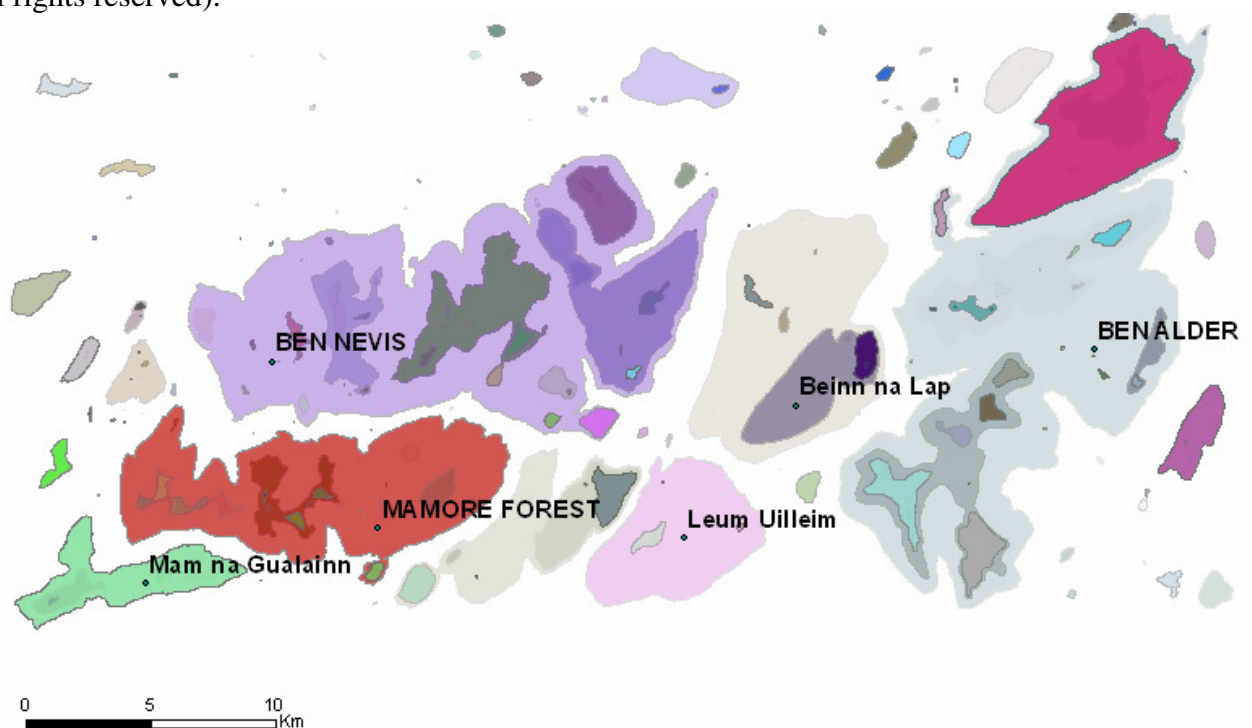


Figure 17: Resultant extents of summits from Figure 16

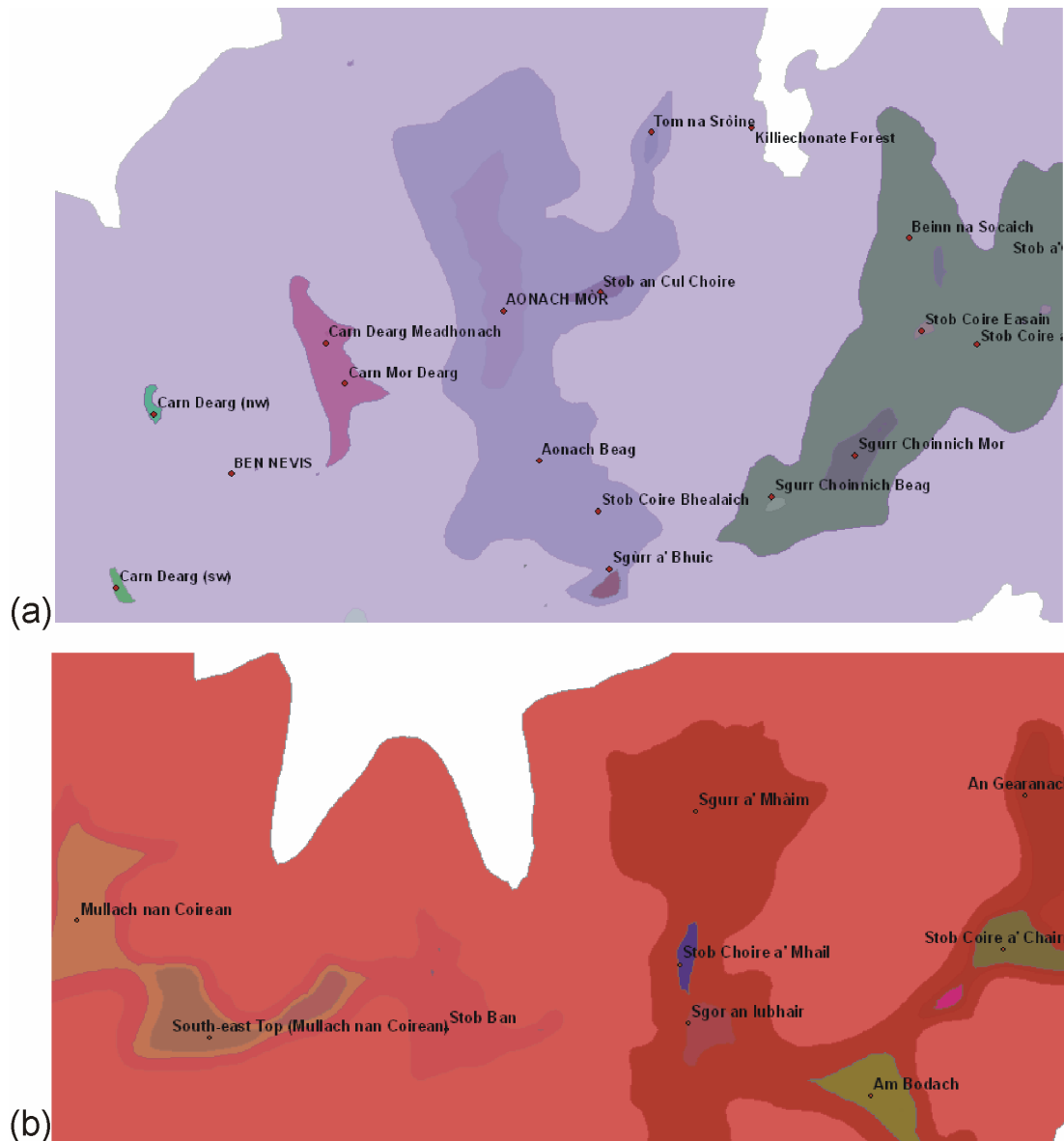


Figure 18: Text points selected from Strategi and the resultant extents of mountains and ranges within two of the ranges in Figure 17 (a) Ben Nevis Range (b) Mamore range

4. Discussion

Using the name points selected from Strategi (1:250 000) we performed an evaluation by checking if the name points lay within the footprint or extent of the resultant hills and ranges. It is important to point out here that the name points selected from Strategi are from a cartographic product. Their inclusion and placement has been influenced by their size, importance, and localised clutteredness. As shown in Figure 15 and 18 most of the text points lie within the boundaries generated whilst others lie outside, and in some cases there is no text associated with the extent. In some cases space constraints have led either to their being omitted, or displaced. It is important to realise that in Strategi there is no ‘link’ between the text points and the places they represent but that the methodology presented here, precisely allows us to do this. It is anticipated that this information can be used by name placement algorithms (Barrault, 1995; Petzold *et al.*, 2003) to determine how much displacement might be tolerated. It can also be used to control orientation, curling and general ‘fitting’ of text to show the extent of a range (for example in the way that the text ‘Southern Uplands’ is placed in Figure 1b to show the shape and extent of this range).

4.1 Spatial Query and Partonomic Structures

Another use of these resultant boundaries is in determining the partonomic relationships among other topographic features. For example, via spatial query we can identify which buildings fall within a hilly region of Edinburgh (Figure 19), or by identifying the minor roads that connect two remote villages via a mountain road, the cartographer can give increased emphasis to its representation. Thus knowledge of these different properties can inform the cartographic process in terms of design constraints and symbolisation.

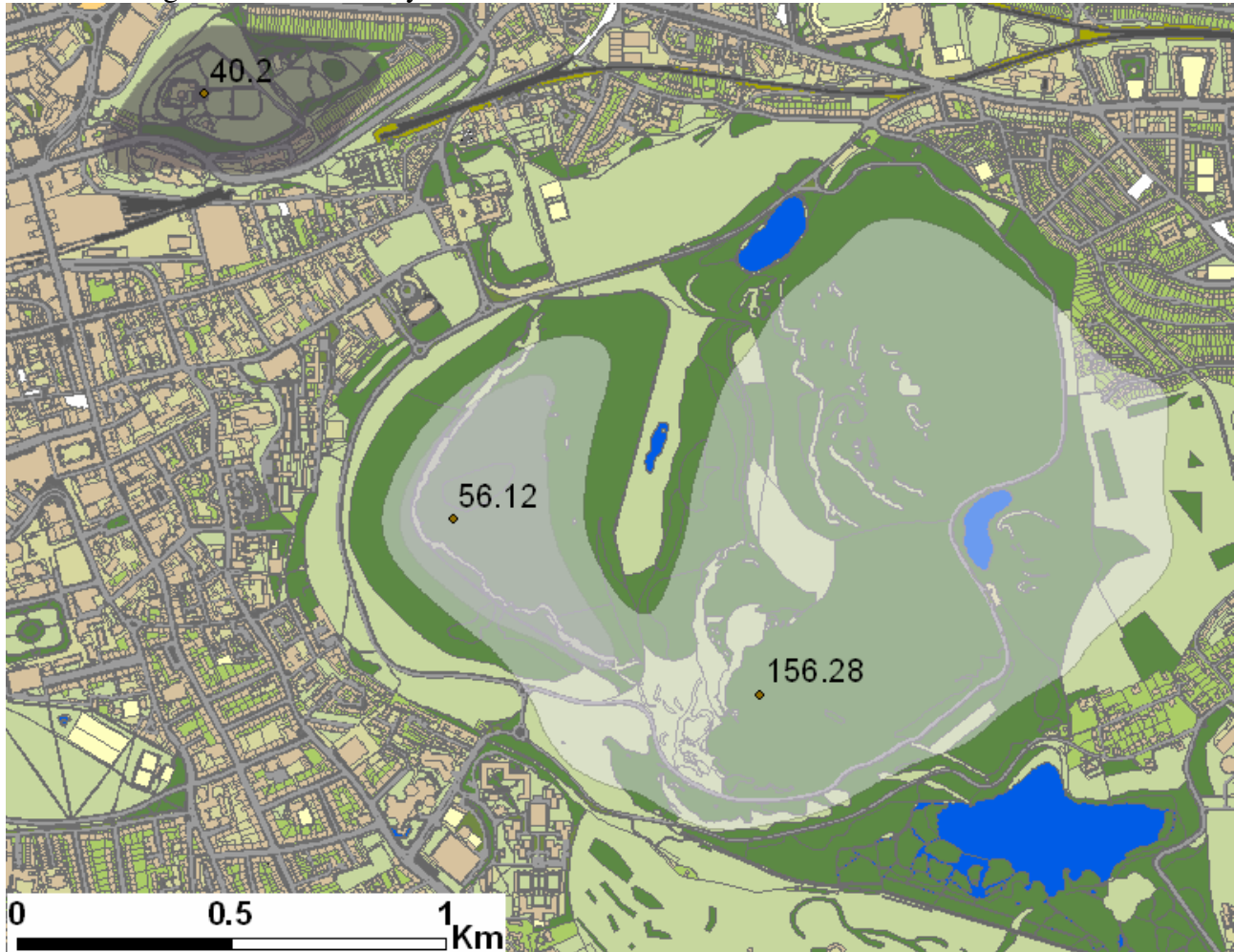


Figure 19: Resultant hill boundaries from overlaid with OS MasterMap[®] Topography Layer, enabling identification of ‘places to live that have a nice view’ (Ordnance Survey © Crown Copyright. All rights reserved).

4.2 Fuzzy Nature of Hill and Range Boundaries

It is worth remembering that in reality the boundaries to hills and ranges are somewhat vague because of the fuzzy nature of the concept (Campari, 1996; Userly, 1996) and because it is difficult to create a discrete boundary when modelling continuous phenomena (Molenaar, 1996). Any statement about real world phenomena need to be defined, understood and described within a certain context of observation (Molenaar, 1993). A lot of research has been undertaken that deals with modelling fuzziness in spatial objects, and in crisp and non crisp boundaries (Campari, 1996; Molenaar, 1993; Molenaar, 1996; Reinke & Hunter, 2002; Winter & Thomas, 2002). Here we have presented an approach for the creation of fiat boundaries for hills and ranges (Smith & Varzi, 2000) based on their morphological properties along with their prominence. In this paper we haven’t modelled the fuzziness in the output boundaries but we believe that the proposed approach can be utilised in the modelling of fuzziness (Cohn & Gotts, 1996; Fisher *et al.*, 2004; Pawlak, 1982; Worboys, 1998) and this offers interesting avenues for future research.

4.3 Utilising SRTM Data

This paper used data provided by the Ordnance Survey as the basis for application and development of the algorithm. In order to demonstrate its broader application, we explored the use of data captured at a lower resolution since the resolution of the DTM can determine whether or not a particular morphological unit is discernible. The Shuttle Radar Topography Mission (SRTM) collected a digital terrain model for 80% of the world (www2.jpl.nasa.gov/srtm/). This data are provided in WGS84 latitude longitude coordinates, is freely available, and has a 90m resolution (3 arc second). It was observed that the SRTM had captured a ‘softer’, smoother, more diffuse surface whilst the Land-Form PROFILE dataset with a 10m resolution has captured a crisp picture of the landscape, recording the morphology of relatively small features. Using different input datasets, varying the amount of smoothing of the input dataset, changing the contour interval used, or altering the threshold of the prominence value; all these variables will have an effect on what summits and hills are identified, and what the extent of a range or summit will be. We would argue that there is no single, perfect DTM resolution or a single, ideal set of parameters. Their appropriateness will depend upon the context of use, and the types of information that the user wishes to portray. For example sometimes the geomorphologist is interested in a fine scale view of the world, whilst at other times they may be interested in macro scale processes and features. From a cartographic point of view, this manifests itself in the representation of different morphological features that become more generalised at smaller and smaller scales. By way of example, Figure 20 and Figure 21 show the results of deriving hills and ranges for the region around Arthur’s Seat in Edinburgh, Scotland using SRTM data and Land-Form PROFILE data. A number of observations are made. The larger cell size of the SRTM data records a spot height of 219.43m and a key contour value of 85m, giving a prominence value of the summit as 134.43m. The smaller cell size associated with Land-Form PROFILE data means that finer detail is recorded – a spot height of 236.28m and a key contour of 80m gives a prominence of 156.28m to the summit. Carlton Hill (with a prominence of 40.2m) was a hill ‘lost’ in the SRTM data, but captured in the Land-Form PROFILE data (Figure 21). Broadly speaking, the two have similar extents, but for larger scales, the Land-Form PROFILE results (Figure 21) are much preferred in terms of their accuracy.

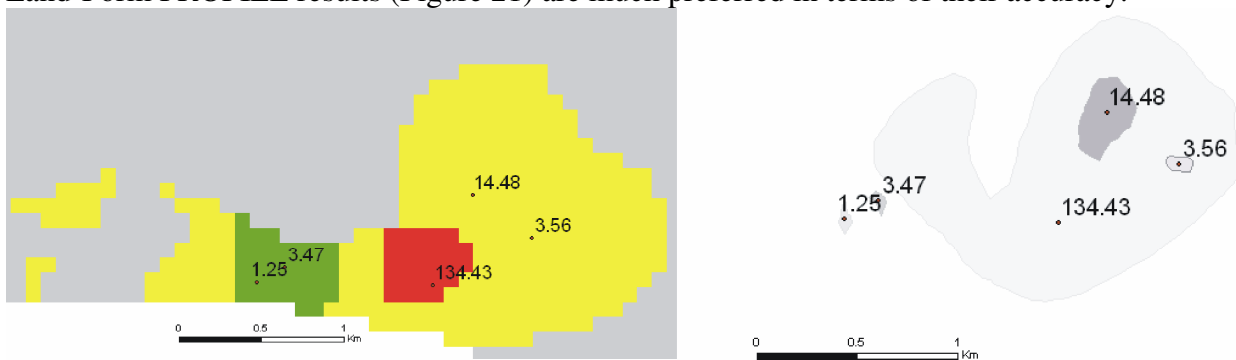


Figure 20: SRTM morphology and results for the region around Arthur’s seat, Edinburgh using the same threshold as for the profile created in Figure 21

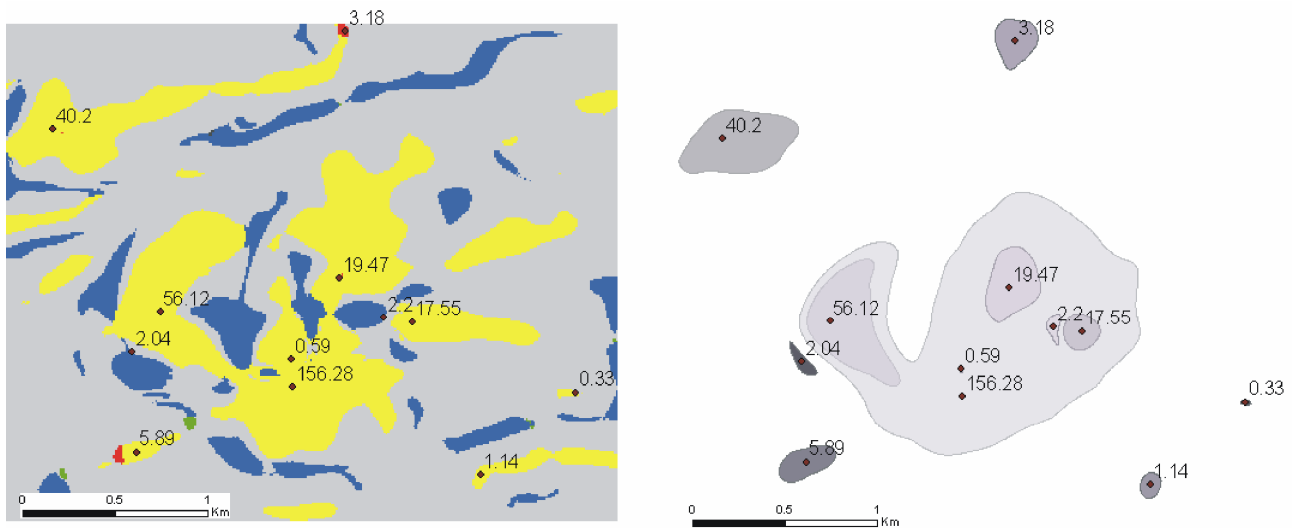


Figure 21: Profile morphology and results for Arthur's seat, Edinburgh

5. Conclusion

In this paper we have demonstrated an approach for determining the extents or boundaries of continuous phenomena such as hills and mountain ranges so that objects representing these concepts can be created and stored in a vector database. We would argue that its novelty lies in combining morphological variability and prominence in determining the extent of summits and ranges. By incorporating this information into multiple representation databases, we have demonstrated how multi scale products can be derived from a single detailed database.

The morphological classification of landscape has application in land capability mapping, and in automatic production of thematic mapping at small scale (say 1:50k – 1:1m). It has important application in semantic reference systems and spatial query and in cartographic generalisation in terms of symbol placement, and in model generalisation in the aggregation of source objects and also for spatial analysis. The proposed methodology has been shown to be successful in derivation of summits and extents in different areas with low and high changes in morphology but there are areas of further study. Firstly the various parameters used in the analysis need to be evaluated further in order to assess how generic the algorithm is for different regions of the world. Future work will therefore look at its application to mountainous regions such as the Alps and the Himalayas using SRTM data (90m resolution). Future work will also examine ideas for modelling the fuzzy nature of such continuous surfaces.

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