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Structuring the Digital Elevation Model into Landform Elements through Watershed Segmentation of Curvature

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1. Introduction

The spatial prediction of landforms and surface processes is an important component in the understanding and modelling of an environmental system. Therefore a fundamental research topic within geomorphometry is to extract and classify landform elements and landform types. The general topic is thoroughly introduced and reviewed in the recent chapter by MacMillan and Shary (2008) and the paper by Minár and Evans (2008), but in this paper the focus is on the matter of automatic extraction of landform elements.

Landform elements are segments characterized by simple geometry and can be viewed upon as the basic building blocks for landforms, landform types and landform systems. While many applications (implicitly or explicitly) define the grid cell itself as the basic landform element, several studies have pointed out the weaknesses of this approach (e.g. Rowbotham and Dudycha 1998, Blaschke and Strobl 2001, Romstad 2001, Dragut and Blaschke 2006). If a landform element instead can be defined by a group of connected cells, we have effectively made the transition from a field based to an object based representation of the terrain. This is a powerful approach as it allows for the calculation of contextual information such as the shape and size of regions. Important contributions on how to construct geomorphologically significant landform elements in this way include those of Friedrich (1996), MacMillan et al. (2004), Dragut and Blaschke (2006) and Strobl (2008).

The by far most common method for this type of terrain segmentation is to delineate local catchments by use of flow modelling. This type of segmentation has the favourable property that the method for delineation of regions is based on an explicitly defined physical process (hydrological flow). Thus the resulting regions represent meaningful real world objects by definition. A weakness is that this method does not ensure the geometric simplicity of the resulting elements and significant changes in slope gradient may have to be treated separately. Dragut and Blaschke (2006) delineated homogenous landform objects by applying the image segmentation algorithm described by Baatz and Schäpe (2000) to a set of topographic attributes. This algorithm convincingly created landform elements that were both geometrically simple and geomorphologically meaningful, but the algorithm is complex and relies on a number of parameters. Thus it may be difficult to predict how the algorithm will behave when applied to the same topographic attributes in different areas.

In this paper we explore whether a simple watershed segmentation of curvature maps will produce meaningful landform units. We explain how this segmentation procedure creates elements that are geometrically simple and we evaluate the method by comparing the resulting regions to a geomorphological map.

2. Method

The general concept of the method is to calculate the mean curvature from a DEM and then create a set of landform elements by applying a watershed segmentation to the curvature image. These landform elements are formed around depressions in curvature and are thus referred to as *concave elements*. A second set of landform elements is then created through a watershed segmentation of the inverse curvature image. As this will result in elements that are formed around curvature peaks we refer to them as *convex elements*. Below follows a more detailed description of each step in the method.

We used a DEM with 20m spatial resolution covering an area of 20×20 km. Before calculating the curvature the DEM was smoothed twice with a 5*5 average filter. This was done in order to reduce the effect of noise and small scale variation in the DEM. Then the *mean curvature* was then calculated for each cell with the method described by Young (Young 1978) and Evans (Evans 1979). The curvature values were expressed in units per 100m and the standard deviation of curvature values in the whole study area was about 0.11. The inverse curvature image was calculated by simply multiplying curvature with -1.

Especially in areas where the curvature is near zero there may be minor fluctuations in curvature values that represent insignificant changes of the surface geometry. This will lead to an over-segmentation of the terrain. In order to resolve this, shallow minima should be suppressed (filled) prior to segmentation. Defining what the minimum watershed depth should be will be dependent of the quality and the resolution of data and also the scale of the analysis. In our study we defined the minimum watershed depth as 10% of the standard deviation of curvature values in the dataset (a depth of about 0.01 $100m^{-1}$) and consequently curvature fluctuations below this magnitude were ignored.

Having suppressed shallow minima in both curvature images the watershed segmentation was applied. We used an algorithm that builds regions around each local minimum by simulating a gradual “flooding” of the image and watershed boundaries are formed where the “water spills over” between two neighbouring basins (Vincent and Soille 1991). The concave elements, which are the regions resulting from the curvature image, represent a cycle of curvature values with the highest values around the edge and the lowest values in its interior. As illustrated in Fig. 1 the shape of the element itself may not necessarily be concave, it could also be a planar slope or a plain that is convex near its boundary. We refer to this as a *false concavity*. Fig. 2 illustrates that the same situations occur for the regions resulting from the inverted curvature image. The convex elements may be truly convex features, or they can be *false convexities*; planar elements that are concave near their boundary.

All calculations were performed with Matlab version 7.6 using the Image Processing Toolbox.

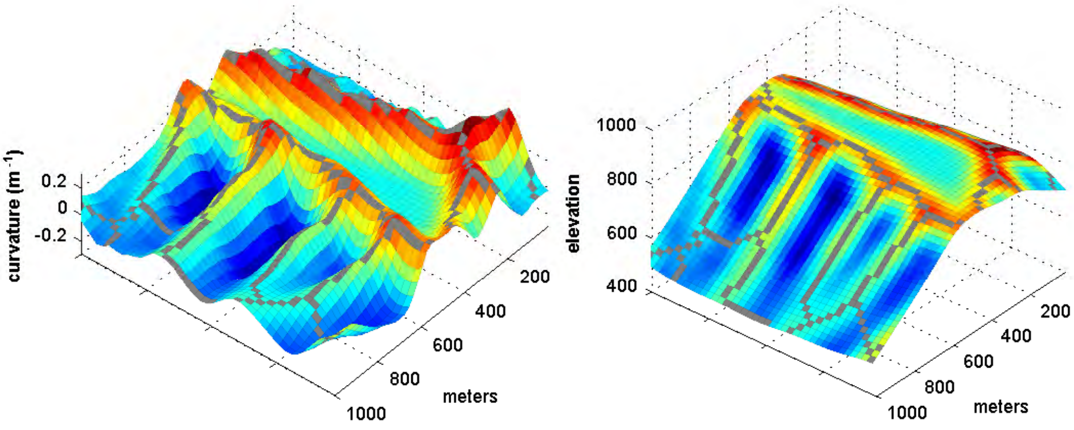

Fig. 1. Illustration of watershed segmentation of curvature (left) and the resulting concave elements draped over the original terrain surface (right).

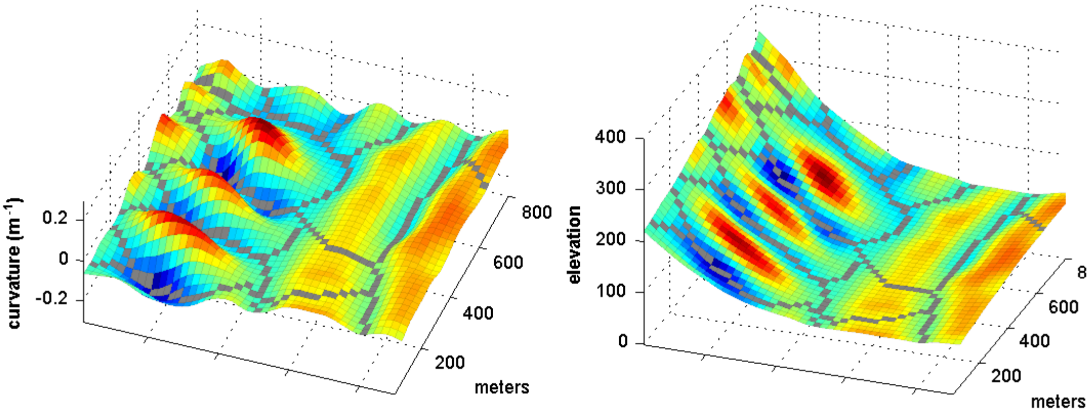

Fig. 2. Illustration of watershed segmentation of *negative* curvature (left) and the resulting convex elements draped over the original terrain surface (right).

3. Results and Discussion

The study area was located in Adventdalen, at 15.8°E and 78.2°N on Spitsbergen island in the Barents sea. This area is characterized by horizontal or slightly dipping Mesozoic sedimentary sediments, incised by both fluvial and glacial valleys with steep slopes. Permafrost is continuous and local glacierisation dominates at present. The area comprises an ensemble of glacial and periglacial landforms and sediments, dominated by gravitational processes along the slopes (talus, debris flows) and sorting processes (patterned ground) on valley bottoms and higher plateaus. To illustrate the potential of the method the regions resulting from the segmentation procedure were evaluated by qualitatively comparing their outline to different landforms and surface material types in a geomorphological map of the area published by The Norwegian Polar Institute (Tolgensbakk et al. 2000).

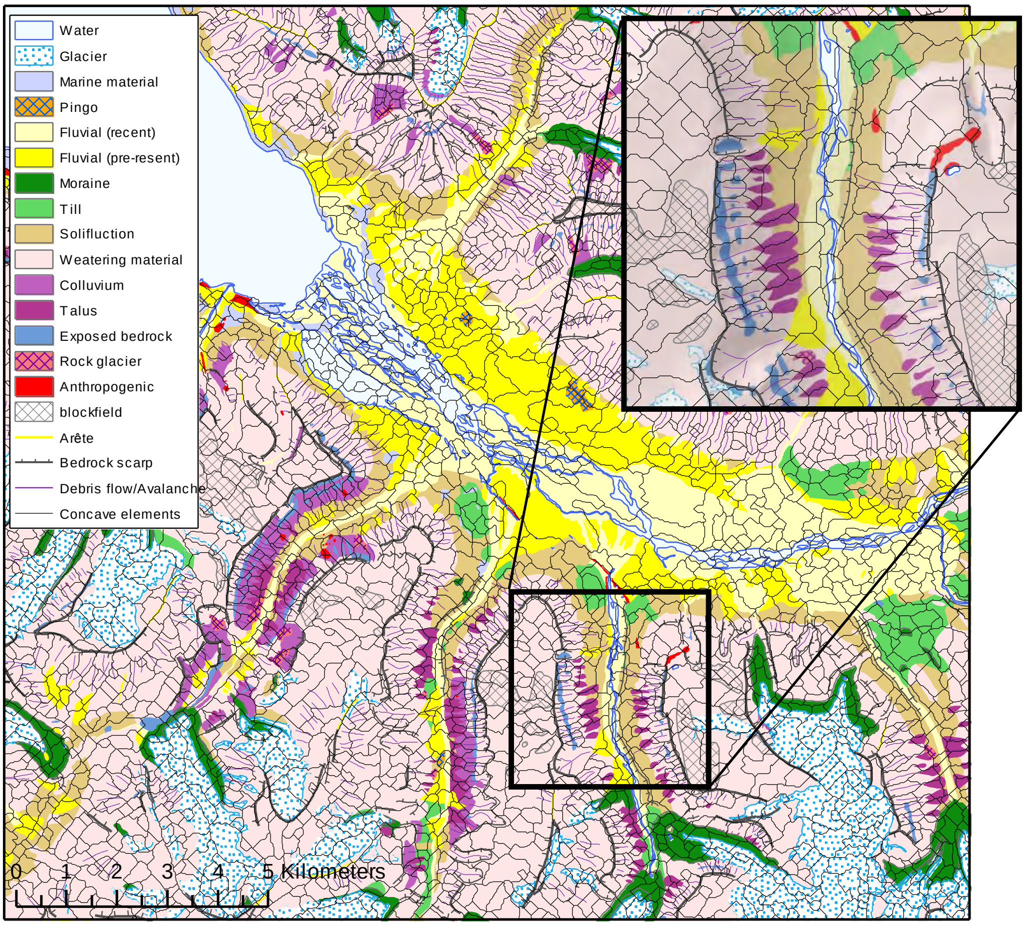

Fig. 3. Geomorphological map over the study area overlaid with concave elements. Detail from one of the valleys inset.

In Fig. 3 concave elements are shown overlaid on the geomorphological map. We observe that individual elements clearly define ravine-like features above talus and alluvial fans. Individual elements also include some larger canyons and to some extent well developed cirques are outlined by individual concave elements. All these are landforms that are typically formed by erosion and net material loss and they have a truly concave geometry. The elements can also be assumed to serve as source areas for material that is removed through mass wasting, fluvial or glacial action. The boundaries of concave elements coincide with bedrock scarps and mountain crests. For this reason isolated plateaus or mesas are well represented by concave elements. These false concavities are successfully delineated by the watershed segmentation algorithm because the convex shoulders (scarps) act as a dam around the non-curved plateau areas.

Convex elements are shown in Fig. 4. Pingos, talus, rock glaciers and some of the steeper alluvial fans are in very good agreement with individual elements. This is expected as these are landforms with a relatively simple geometry and they also have a truly convex shape. The latter is also true for mountain edges and moraines, but we observe that these landforms are split up into several elements due to undulations along the length direction. The boundary of each moraine is more or less continuously overlapped by a region boundary.

Elements in the areas described with broader surface material types (fluvial, till, solifluction, weathering material) are typically false convexities formed around planar surfaces bordered by footslopes. The footslopes define the transition from one process domain to another and thus the boundaries of the elements coincide with the boundaries in the geomorphological map.

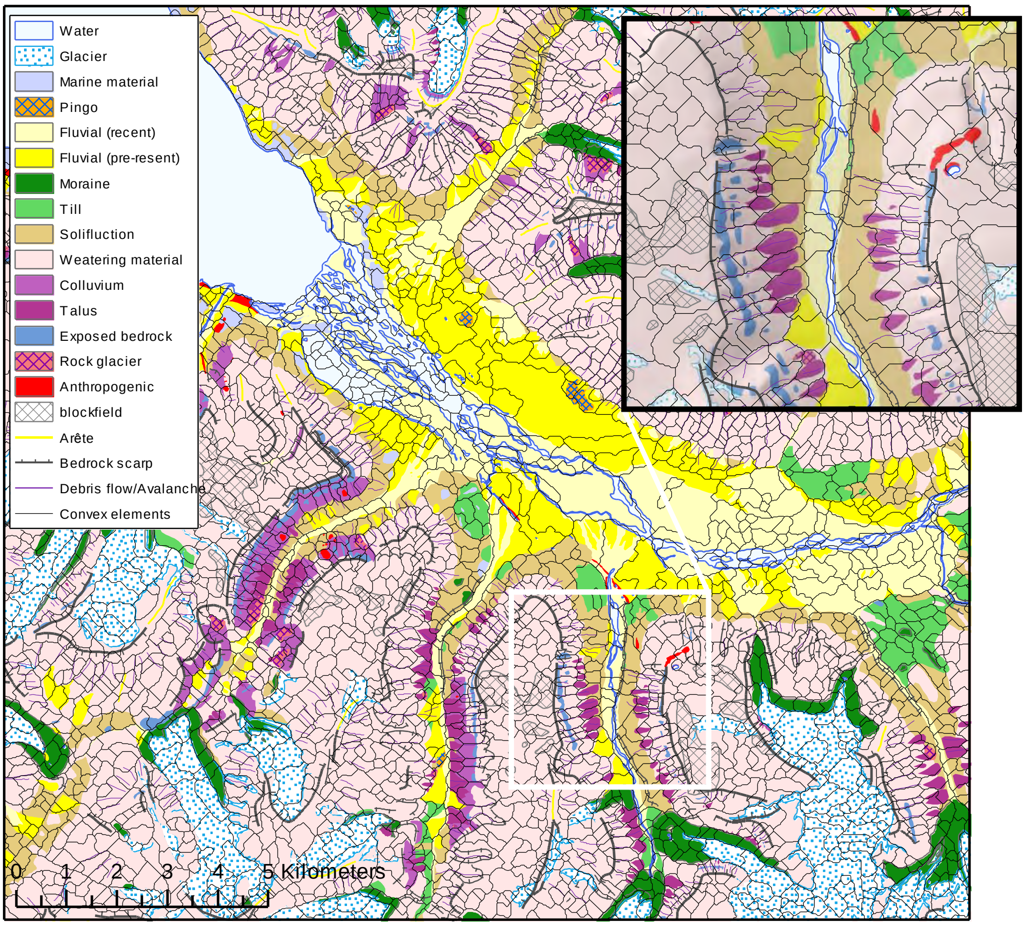

Fig. 4. Geomorphological map over the study area overlaid with convex elements. Detail from one of the valleys inset.

In general boundaries between different landforms or surface material types are respected by either the concave or the convex elements. This implies that uniform geomorphological processes can be assumed within sub elements resulting from the combination of the two sets. Each of these sub elements may be described by a combination of its own properties (geometry, shape, size...) and the properties of the concave and convex elements to which it belongs. As uniform surface processes can be assumed within each element they are suitable as spatial units in earth system modelling and analysis, e.g. in spatial modelling of slope stability, erosion processes or ground thermal regimes and freeze/thaw depth estimations.

4. Conclusions

We have presented a terrain segmentation method that is conceptually simple and makes use of computationally efficient algorithms that are implemented in most GIS. By its nature the method produces landform elements with a geometric simplicity. The elements are either characterised as curved slopes or as planar slopes or plains bordered by footslopes or shoulders. The analysis showed that the elements correspond well with the landforms and surface types represented in the geomorphological map.

Much the same way an ordinary watershed segmentation of the digital elevation model can be used to define hydrological response units a watershed segmentation of curvature may be a powerful and efficient way to define geomorphological process units. Terrain segmentation using this method is therefore expected to be meaningful for a number of applications and the method may be particularly suitable when the geomorphic objects of interest are characterized by a cyclic variation in topographical attribute.

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