Defining Landscape Units Through Integrated Morphometric Characteristics

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Abstract

Landscape analysis and landscape planning need sophisticated spatio-temporal image analysis complemented with context-sensitive methodology. The latter means that raster processing has to evolve beyond per-cell analysis. We have integrated two approaches for the delineation of homogenous areas, or “mapping units”. First, a multiscale image analysis technique is used to extract objects from earth observation images. Using multiscale segmentation and object aggregation, homogeneous ‘patches’ are created comparable to those produced via manual interpretation. However, a benefit of the approach is that constituent lower level (i.e. finer resolution) objects are available plus the patch delineation process is explicitly parameterized. These rules (including fuzzy operators) are stored in the project, and can readily be queried and modified when a new understanding of the mapped scene is introduced. We assume that mapped boundaries are based on ontological objects, corresponding to real world entities of scientific and practical significance. Second, we apply segmentation methods to terrain information and add this information to the patch definition algorithms. This enables us to combine boundary characteristics (length, relative proportions to neighbours, spectral gradients to neighbours etc.) with object characteristics (mean spectral as well as elevation and morphometric values, standard deviation, range) and sub-object information (e.g. heterogeneity based on sub-objects, spatial distribution of subobjects). Morphographic landform information is essential for the modeling and the understanding of many physical processes. Analysing geomorphological processes, surface runoff and erosion as well as mass movement risk assessment and microclimatology require consideration of topographic features. We demonstrate that the combination of these methodologies allows for better detection and mapping of complex topographic land-use units and, by incorporating patch generation rules, for improved landscape monitoring and scenario modeling.

1 Introduction

Physical processes frequently are focused on contiguous regions, often structured into hierarchical systems. Some of these regions can be identified rather easily (e.g. hydrographic catchment areas) but in many cases do not have crisp and obvious boundaries. We see an increasing demand for a delineation of landscape units for spatial planning tasks and take the challenge to bridge GIS/image processing tools and landscape ecological applications but restrict ourselves in this article to methodological research questions.

With the terms ‘landscape analysis’ and ‘landscape modeling’ we refer to a landscape level consideration of spatial entities. The North American approach of landscape ecology (FORMAN 1995) has provided the foundation for spatial analysis at a landscape level and this approach builds the basis for several planning methodologies (LEITAO & AHERN 2002). The key for us is the spatially explicit consideration of landscapes and their constituting entities opposed to a quantitative consideration of land use statistics (“12% of the landscape belongs to the class <urban, sub-urban>). The evolving landscape metrics, (BLASCHKE 2000) is becoming more widespread. It addresses landscape patterns which are based on the underlying geometry (shape, size, fractal dimension, compactness etc.) of landscape units or patches and their spatial arrangement, interspersion, juxtaposition, diversity etc. (FORMAN 1995). But this methodology is almost completely limited to a 2-dimensional view of the landscape. In this paper, we want to extend the concept of landscape units to units based on terrain information and geomorphological parameters. Depending on the specific research domains and objectives, landscape units shall be defined by using various descriptive terrain metrics, such as elevation, slope, aspect or curvature. There is a growing number of algorithms and software packages available to derive theses parameters although simple parameters such as curvature or even slope are far from standardization.

Scale is a prominent issue throughout spatial disciplines. Landscape as well as terrain processes are essentially multi-scale phenomena. While varying raster resolution is only a very coarse means of differentiating levels of scale, nested multi-level segmentation takes well care of scale levels with their associated changes in heterogeneity, aggregation hierarchies of measurements and generalization of conceptual views (like entries for legend terms etc.).

With the methodology outlined in this paper we aim for a flexible framework to serve several needs. By using multivariate segmentation techniques, polygonal region outlines are created on multiple nested scale levels. The spatial entities at these levels provide the basic building blocks for modeling physical processes and systems.

DEM’s are today increasingly available from multiple sources with very different measurement characteristics and levels of resolution: satellite and aerial radar interferometry is complemented with high resolution laser scanning, replacing the more traditional means of photogrammetric techniques. Large-area coverage at multiple resolutions is thus more easily accomplished, making high quality (better than one meter vertical accuracy) elevation data available for integrated landscape analysis.

In this paper, our objective is to verify whether multi-level analysis approaches used in a real world study can reflect specific landforms and land use entities through incorporating semantic rules based on e.g. form, size or texture of landscape objects. We start from image and terrain analysis methods. Only recently, geomorphological analysis functionality has been integrated into operational GIS environments. Technically, Geographic Information Systems (GIS) allow us to overlay different kinds of information but we obviously need information based on ecologically meaningful spatial units. While GIS provide many algorithms for data integration and analysis the limiting factor is often the lack of a methodological framework for integration of environmental data on different levels flexible enough to accommodate multiple research questions. We demonstrate that object-oriented analysis of digital terrain models provides an entirely new pathway into the spatial analysis of landform-dependent phenomena and processes. Finally, we compare our empirical results with an expert maps through overlay analysis.

2 Methodology

2.1 The Need to Delineate Landscape (Ecological) Units

For many reasons we are all the time trying to break down complexity by delineating relatively homogeneous areas. But the word 'relative' indicates there is only a certain aspect under which a subset of a landscape or and ecosystem can be considered to be homogeneous. But complex systems exhibit a high degree of heterogeneity in both time and space. Consequently, complex systems are often characterized by emergent properties, multiscale interactions, unexpected behaviors, and self-organization (PRIGOGINE 1997). (Eastern) German landscape ecology (HAASE 1989) created a framework of natural structuration ('Naturräumliche Gliederung'). There are too many other approaches of delineating spatial units for planning purposes as we could discuss herein. Instead, we claim the landscape as a concept is bedevilled by semantic differences and many misunderstanding. Despite this, several common interpretations of the term landscape can be deciphered. Landscape Ecologists and some Landscape Architects use the word as if it is synonymous with the word "environment". In this context it has been defined as "the total spatial and visual entity of human living space, integrating the geosphere with the biosphere and the noospheric man-made artefacts" (NAVEH & LIEBERMAN 1994, p.4). Within physical geography, "landscape" has often been used in relation to the physiographic, geological, and geomorphological features of the earth's crust (NAVEH & LIEBERMAN 1994). In this context the word "landform" or "topography" would be more exact and is used by most physical geographers.

In everyday language, our understanding of landscape is closely tied to terrain features. When delineating landscape entities we will intuitively draw boundaries at any prominent change in topography like ridgelines, breaks in slope or curvature. Thus clearly 2D processing as we know it from spectral image analysis is not up to the job of properly identifying landscape units in any but completely flat terrain. Taking into account topographic objects for higher level landscape unit definition is a main objective of our work.

2.2 Introducing an Object-Oriented Landscape Analysis Methodology Based on Multiscale Segmentation

While GIS may be regarded as a technically mature approach, the operational use of remote sensing is hampered today by the lack of a sound methodology to reliably and reproducibly gain semantics-rich information from reflectance data. Recently, object-oriented image processing approaches have been introduced based on image segmentation techniques. More specifically, we refer to multiscale image segmentation as introduced by BAATZ & SCHÄPE (2000) and as implemented in a commercial software environment. Although image segmentation is not new, the idea to create objects based on topological and shape information is still the exception in the remote sensing world. Very few applications combining spectral and topographic information through object creation exist (ALMEIDA et al. 1997, SCHIEWE 2002)). It is hypothesized that this methodology enables us to better move from 2-D object cognition based on remote sensing images only into the realm of 2.5D objects. The challenge and flexibility of the multi-scale segmentation approach lies in the definition of semantic rules relating lower level landscape units or 'holons' to higher levels of organization. Several studies have demonstrated the potential to overcome the subjectivity in the definition of objects of interest. This research was restricted to the use of remote sensing information and auxiliary GIS information as the respective input data.

We use the methodology of segmentation-based object modeling laid out by BURNETT& BLASCHKE (2003) based on the theory of hierarchical patch dynamics paradigm (WU & LOUCKS 1995). First, in a segmentation step, a fractal-based multi-scale segmentation algorithm developed by BAATZ & SCHÄPE (2000) is employed. The Fractal Net Evolution Algorithm (FNEA) has already successfully been applied in other studies (see BLASCHKE & STROBL 2001 for an overview) and is based on assessments of homogeneity and heterogeneity. In it, an iterative heuristic optimization procedure is programmed to get the lowest possible overall heterogeneity across an image. The basis for this is the degree of difference between two regions. As this difference decreases, the similarity of the two regions is said to be closer. In the FNEA, these differences are optimized in a heuristic process by comparing the attributes of the regions (BAATZ & SCHÄPE 2000). Given a certain feature space, two image-objects are considered similar when they are near to each other in feature space. In a second step, the semantic links between image objects are established based on principles of object-oriented programming which allow to semantically express intrinsic spatial and spectral relationships such as: 'an object is constituted by certain sub-objects', 'sub-objects are elements of super-objects', 'sub-objects inherit certain characteristics from their respective super-objects' and vice versa. This is just a very brief description of object-oriented image processing, for more details see BAATZ & SCHÄPE (2000) or BLASCHKE & STROBL (2001). In the following study, we apply this methodology to terrain information, as conceptually laid out by STROBL (2001) and BLASCHKE (2002).

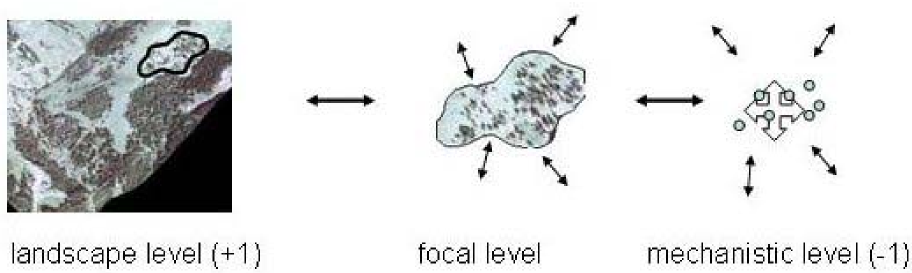

Fig. 1: Basic principle of multiscale, oo image analysis: Information is gained and explicitly expressed through objects, their respective super-objects (here only one level above the 'focal level' is shown) their respective sub-objects (here single trees) and specific characteristics of the subobjects such as their spatial arrangement, distribution, shape, size, spectral characteristics and many derived products from shape/area/distance relationships.

2.3 Digital Terrain Analysis

In the 1990's there was a dramatic change in the utility and power of GIS because of advancements in computer hardware, as well as improvements in the GIS software, but most importantly: because of the development of theories and methodologies. Digital analysis of terrain data is not new (see ZEVENBERGEN & THORNE 1987), dedicated terrain analysis systems have been developed by researchers from various backgrounds as demonstrated by DIKAU (1990); VIVEK et al. (o.J.), or KNOWLEDGE SCIENCES INC. (o.J.). While all of these approaches start from morphometric terrain description and some require the manual identification of surface-specific points (peaks, saddles) or linear featues (ridges, rivers), they are not fully capable of providing flexible, explicitly parameterized, multi-scalar terrain unit identification, not to mention the optional integration with spectral information from remote sensing imagery.

Many previous approaches to the terrain-unit-identification problem were starting from hydrological requirements. The identification of a nested hierarchy of catchments is a specific task which had been successfully solved after having dealt with the issue of spurious pits in terrain data. As those catchment units a defined with the sole task of quantifying and routing runoff, these tools cannot be generalized for other purposes of landscape study.

In several cases the keyword of 'segmentation' is used rather liberally for any type of patch- or region-based identification of sub-units within study areas. While of course a catchment, an elevation zone or one slope can be termed a segment, it needs to be pointed out that for the purpose of our work 'segmentation' is understood as outlines by Baatz and Schäpe, 2000, with our core concept being the transfer of this methodology into studies of topographic and landscape units.

In general, we can distinguish between goal-oriented landscape classification and 'neutral' landscape description. Classification groups objects into discrete categories, while description expresses the variation over one or several factors like slope, rate of slope change, frequency of slope change etc. Description has been the traditionally means of communicating about landscapes. It describes a particular landscape in a way that conveys a clear picture (e.g. 'rolling hills'). This approach is commonly used by Landscape Architects for analyzing a site for a proposed development, or by writers who try to evoke the character of particular landscape in literature (BRABYN 1996). However, description can be an inefficient means of evaluating landscapes for specific landscape planning tasks where categories and thresholds are needed, e.g. for suitability studies or zoning plans.

Classification is important to science because it provides a transferable frame of reference that enables different researchers to communicate their results effectively. It also helps order and structure what is known (HAINES-YOUNG & PETCH 1986). In fact, classification is an important part of cognition and the importance of classification for landscape research is well known. The perception-oriented approach to landscape assessment is based on a landscape classification. Without classification the approach would be of limited use. Without a landscape classification, landscape researchers are somehow limited to communicate their discoveries, and as a result a body of theoretical knowledge will be slow to develop. Still, for this study, we stick to a 'neutral' descriptive approach and compare the results with existing manually classified data. This is because any landscape classification has to start from the specific purposes such a classification is going to serve.

3 Case Study in the Austrian Alps

While integrated landscape classification will have to involve a combination of spectral as well as morphometric layers to properly identify and characterize landscape units, the currently more critical research topic is to explore the identification of terrain units based on morphometric descriptors. While the behaviour and distribution of spectral data are well understood, terrain morphometry exhibits quite different characteristics:

- Slope, azimut, elevation, curvature etc are typically all calculated on different scale ranges and have to be adjusted to avoid implicit weighting effects during segmentation
- Azimut is a cyclical variable (0° equals 360°!) and needs special attential
- Curvature is a bi-directional variable with an important neutral point at 0
- Distribution of all descriptors changes substantially by study area and typically is far from normal, uni-modal or symmetric

Depending on software used a number of adjustments and weighting factors have to be set to make sure that contributions from these factors to the identification of terrain units is properly and explicitly controlled. Objectives for terrain segmentation are

- Delineate multi-level topographic segments from continuous surfaces based on morphometric characteristics
- (Fuzzy) classify these segments into terrain units with regard to specific applications
- Support application-specific modeling tasks based on clearly defined and reproducible terrain units

One example of an already well adjusted segmentation-plus-classification result is demonstrated with the graphic below. If, for instance, elevation (ranging between 500 and 2500m in this area) would not be weighted much lower than e.g. slope measured in degrees, all terrain units would be very strongly oriented along contour lines. The understanding of topographic classification into terrain unit is by now well developed and the authors have been able to progress towards the stage when application-specific definitions for classifications can be developed.

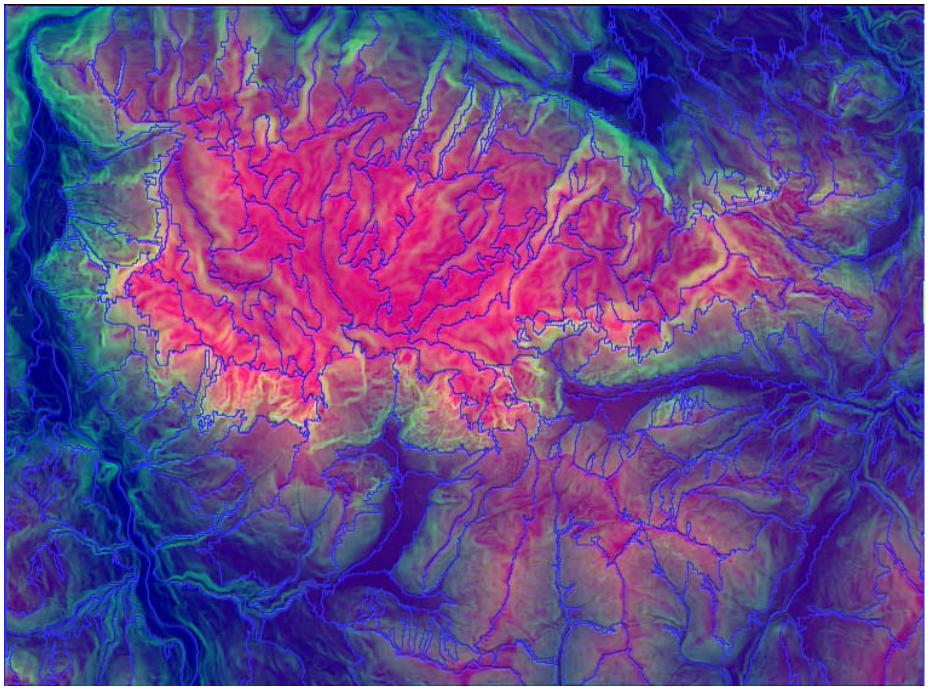

Fig. 2: Sample terrain classification based on morphometric characteristics for a study area in the Tennengebirge mountains, Austria, based on a 25m DEM only.

As indicated above there is two additional steps to be taken in order to apply terrain-based segmentation and classification methodology in landscape research. First, any modeling can only be properly designed and adjusted when it aims at a known purpose within a defined application domain. When we are looking at the wider framework of a research workflow (see schematic graph below) we have to recognize the requirements of specific application domains first in order to properly parameterize the scaling, weighting and classification elements of terrain unit delineation,

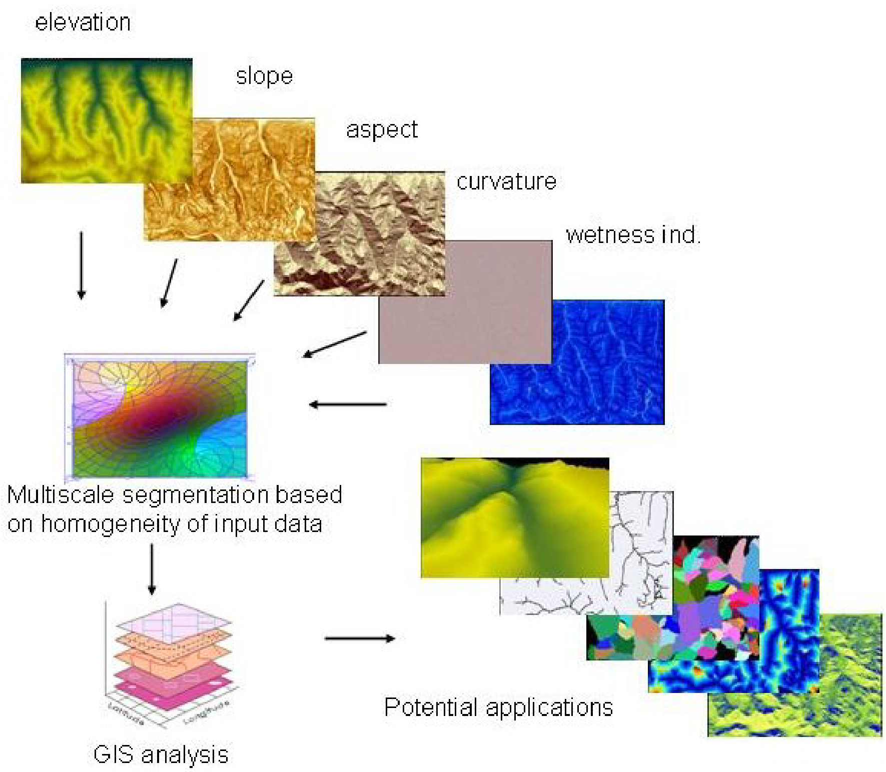

Fig. 3: Research workflow

Next, of course we need to keep in mind there is more to any landscape unit than just landform. While this is a key factor contributing to process dynamics, results from processes manifest themselves in a range of conditions typically read from spectrally differentiated image information. Ultimately, morphometric factors together with remotely sensed spectral reflectance measurements will need to be integrated into adequate classifications of landscape units.

Looking at the below inserted example from a manual delineation of morphologically as well as ecologically determined landscape units (DOLLINGER 1998), this perspective provides aims for next steps in this research: supporting specific application domains with adequate models for exploring their inherent processes and patterns.

4 Results and Discussion

The aim of this paper was to examine how DEM information can be processed in an integrated RS/GIS object-based methodology in order to characterize landscapes, and more specifically, now to algorithmically delineate landscape units based on morphometric parameters derived from DEMs. This study has demonstrated some of the potential with which our segmentation-based methodology can manipulate and analyse information traditionally read from hard copy maps or classic stereo image interpretation. Most measurements as well as complex interpretation and cognition results that can be obtained visually from a map can now be reproduced algorithmically. Furthermore, GIS functionality opens new ways to incorporate topological relations, distance-area relationships and further external information into the process of defining landscape units. The automation of cartographic analysis significantly enhances the geographer's analytical opportunities.

Of course there is substantial need for further research as already indicated above. Selection of input descriptors (‘morphometric bands) as well as algorithms used for their calculation potentially influences results as does explicit weighting of layers, scaling and ‘spatial dimensioning’ of segmentation as well as deciding on nesting levels (not even touching the subject of whether to possibly change parametrization between different scale levels!

Another issue is the weighting of shape characteristics (‘forcing’ of compact and / or smooth vs. elongated and rough shapes) for different types of landscapes. Glacially vs. fluvially formed landscape will differ substantially on the typical forms and shapes of homogeneous units. We believe – but yet have not prooved empirically – that topographic heterogeneity is an important factor for many functions and processes.

Overall, the results demonstrated in this paper make a clear case for further pursuing the refinement and validation of a methodology for segmentation-based multi-level classification of topographic surfaces, where complex terrain units can be derived from morphometric descriptors as well as additional spectral indicators.

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