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**Modeling alpine geomorphology using laser altimetry data**

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## Summary

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Recent developments of data acquisition technology and processing led to renewed opportunities in geomorphological research. However, many established analysis techniques are not designed to deal with the high, and still increasing, detail of modern data sets. It is within this context that the objective of this thesis is to develop new methods for the application of high-resolution topographic data, more specifically, Light Detection And Ranging (LiDAR) data, for geomorphological mapping and dynamic modeling of landscape evolution in a complex mountainous area (Vorarlberg, W-Austria). A key aspect is the strong interaction between expert knowledge and digital analysis techniques.

The first chapters (2–5) focus on the semi-automated extraction and mapping of geomorphological features in mountainous areas from LiDAR data with Object-Based Image Analysis. The geomorphological features include a selection of glacial, fluvial, gravitational and karst features which together cover approximately 99% of the area. The extraction procedure makes use of multiple terrain derivatives, or Land Surface Parameters (LSPs). Especially slope angle, topographic openness, and relative elevation were found valuable LSPs for the identification, delineation and classification of landforms. Slope angle and topographic openness were found to be useful for segmentation, i.e. to formulate objects (which represent land elements) by aggregating homogeneous LSP grid cells. Other properties such as relative elevation, upstream area, length/width ratio of objects, distance to a river, etc. are examples of criteria which have been used for the classification of the objects.

A major concern of current methods that rely on OBIA is the manual fine-tuning of segmentation parameters. Objects form the basis of a landform classification, and their accurate formation is crucial for creating high-quality maps. The research described in Chapter 2 contributes to automating the segmentation by optimizing the ‘scale parameter’, the key parameter that influences the size of objects. By combining slope angle with topographic openness into false-color RGB composite maps the visual interpretation of various LSPs became possible and training samples of the different geomorphological features could be delineated. The frequency distributions of LSP grid cell values that are enclosed by the training samples were compared with those distributions from segmented objects. The difference between both frequency distributions of training samples and objects were used as a measure to assess the segmentation accuracy and optimize scale parameter values. The results suggest that the proposed segmentation accuracy assessment was valuable for the evaluation of objects prior to classification, and that different geomorphological feature types have different optimal segmentation parameters. This led to formulate feature-dependent parameters that have been implemented in a new approach of semi-automated geomorphological mapping using stratified feature extraction.

In continuation of these developments, stratified object-based image analysis was implemented in a protocol on digital geomorphological mapping in mountainous areas (Chapter 3). The protocol has two main phases, namely 1) collecting field data in representative areas; and 2) extrapolating geomorphological feature characteristics to surrounding areas using object-based digital terrain

analysis. The first phase consists a) manually differentiating landform units and digitizing these as polygons in GIS by using 2D and 3D visualization of DTM-derived terrain properties in combination with (multi-temporal) orthorectified air photos, and b) field-validation of these digitized features to produce a digital geomorphological map of the representative areas. The second phase consists four steps, i.e. a) image segmentation and optimization of segmentation parameters for different geomorphological feature types; b) classification rules development by histogram analysis using the representative polygons; c) stratified feature type extraction, and; d) validation of the classification results. We demonstrated the protocol by semi-automatically extracting 11 well-defined geomorphological feature types at the scale of 1:10,000 in the study area near Lech, Vorarlberg. Our results suggest that with only a limited field campaign, we are able to rapidly produce a digital geomorphological map of a large area in a dynamic mountain region. The transparency and reproducibility of the protocol allows application in similar mountain areas and, potentially, also in other environments.

In Chapter 4 the protocol was applied to semi-automatically assess geoconservation value in Lech, Vorarlberg (Chapter 4). The protocol have been supplemented with dedicated field investigations and manual mapping so that high map accuracy can be guaranteed. As a result a ‘hybrid’ map was constructed that was used as basis to the assessment of geoconservation value. Each polygon was systematically evaluated with weighting and ranking criteria related to ‘scientific relevance’, ‘frequency of occurrence’, and ‘environmental vulnerability’ to determine a potential geoconservation score. In total more than 15,000 geomorphological features in approximately 9 km<sup>2</sup> have been mapped and analyzed, of which respectively 1349 (606 *ha*) and 1222 (290 *ha*) features were identified with medium and high significance. Hybrid mapping was found a useful tool for efficient geomorphological mapping and speeds up applied research.

The protocol of Chapter 3 was also applied to a multi-temporal data set in order to test the method for detecting and quantifying geomorphological change (Chapter 5). In our test area on a mountain slope in the Gargellen Valley in western Austria, point data from two airborne LiDAR campaigns of 2003 and 2011 were filtered and interpolated into two 2 m DTMs. Seven geomorphological features were mapped by using the mentioned protocol. Segmentation parameters and classification rules were applied to both data sets so that potential change in the geomorphological functioning of an area could be visualized. Also volumetric change, as derived from the subtracted DTMs, between the geomorphological categories was calculated. The multi-temporal landform classifications show the development of landforms and related geomorphological activity. While a promising tool, differences in point densities and lack of data points below heavily forested areas hindered accurate geomorphological change detection. We suggest using data sets with similar point densities, in low–medium forested areas, and include the assessment spatial DTM error distribution to validate change detection results.

While maps are models that describe the geomorphological setting of an area at one moment in time, dynamic simulation models are valuable tools for increasing the understanding of geomorphological processes and their impact on the environment over time. Many established simulation models are not designed for the immense amount of data that is stored in LiDAR data, thus data reduction is required at the cost of the size of the study area or its detail. At some occasions however, one would require both high spatial detail and in a large study area. In Chapter 6 a landscape evolution model was decoupled into two geomorphological models with two different model strategies and scales, but which interact at specific moments in time. The first model was a vector channel incision model (CIM) which used 1 m LiDAR data for simulating longitudinal profile development. The CIM was combined with a grid cell-based hillslope erosion model to incorporate the hillslope response to incising bedrock rivers in a simulation of landscape evolution. The combined simulation model was applied to a geologically diverse Alpine catchment to simulate landscape development from reconstructed late glacial conditions towards the current

situation. The model is time-efficient and realistically adapts to contrasting geological substrata, while spatially and temporally variable incision values, knick-point recession and variable hillslope development result in a realistic simulation of post-glacial landscape evolution. It was concluded that high-resolution elevation data, in combination with dynamic geomorphological simulation models, facilitate research of complex and difficult-to-access Alpine terrain at greater detail than before.

Model dynamics and results are evaluated mostly on the basis of interpreting topographic change over a digital surface or longitudinal channel profiles. Geomorphometrical analysis and landform classifications are, on the other hand, valuable tools for automated identification and characterization of geomorphological features at one particular moment in time. In Chapter 7, which makes up the synthesis of this thesis, landform classifications are integrated with dynamic landscape evolution models to visualize and evaluate model dynamics. A modular erosion/sedimentation model was introduced to simulate post-glacial landscape development in a small alpine catchment. This model consists of three different modules. Each module describes different geomorphological processes, i.e. the 1) mechanical weathering of bedrock and production, transportation and deposition of debris through rock fall, 2) fluvial erosion of converging water streams by incision into bedrock, and 3) redistribution of unconsolidated materials through superficial flow and slide processes. Model results are subjected to object-based landform classifications and visualized to interpret the dynamics of the model. Here, segmentation and classification parameters were developed based on the initial landscape setting so that individual landforms were identified, extracted, and categorized into morphogenetic classes. The segmentation and classification procedures were applied at several time steps of simulated landscape development. The sequential landform classifications clearly showed the development of fluvial erosion channels which accelerated mechanical weathering and rock fall. The classifications allowed the analysis of simulated topographic change per landform type and revealed a transition from a glacial towards a fluvial landscape in a quantitative fashion. The classifications showed that fluvial erosion acts as a driving force of landscape development. It was concluded that simple criteria for the classification of landscape objects into functional landforms enables a quick but detailed overview of simulation results and model behavior. Using landform classifications we partly automated the interpretation which allowed the investigation of the change of the functioning of a landscape during a simulation. Integrating landform classifications in landscape evolution modeling opens up new opportunities for e.g. evaluating complex dynamics in landscape evolution models, or analyzing scenario-based landscape development and specific landform evolution.

This thesis partly fills a gap between continuously improving computational infrastructure and Earth scientific knowledge. Expanding this interaction is of utmost importance to keep increasing our insights on the functioning of geo-ecological systems and the protection of our unique, yet, fragile environment.