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Geomorphometric Analyses of LiDAR Digital Terrain Models as Input for Digital Soil Mapping

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1. Introduction

The delineation of supposedly homogeneous soil units for the production of high-quality soil maps usually involves intensive field work and requires comprehensive expert knowledge.

There is a need for automated, timesaving and more objective methods of digital soil mapping, which are based on available data on soil forming factors and demand only little additional field work (see McBratney et al. 2003, Lagacherie et al. 2006). This study investigates the applicability of airborne LiDAR (Light Detection and Ranging) data to delineate entities relevant for digital soil mapping using an object-based image analysis (OBIA) approach. Possible improvements of accuracy compared to the use of coarser relief data shall be exemplified.

1.1 Geomorphometrics in Digital Soil Mapping

Relief as one of the soil-forming factors identified by Jenny (1941) plays an important role in digital soil mapping. Relief data derived from digital terrain models (DTM) are used to predict soil classes and soil attributes in 80 % of the studies examined by McBratney et al. (2003). Dobos and Hengl (2008) summarise which and how surface parameters can be utilised as an input for digital soil mapping.

In mountain ranges like the Alps relief has direct (e.g., erosion and accumulation processes) and indirect impacts (e.g., distribution of unconsolidated parent material; hydrological conditions; changes of vegetation, micro-climate and land use) on soil formation, that have to be taken into account in digital soil mapping approaches (Geitner et al. 2009). Friedrich (1996) and Behrens and Scholten (2006) emphasise the importance of the relief as a major driving force in soil formation in European mid-latitude landscapes due to the topographic effects on the distribution of periglacial slope deposits.

1.2 Application of LiDAR Data

Transition zones between landform elements on a meso-scale (e.g., areas at the bottom of a slope, river terraces and embankments) tend to be blurred in conventional raster DTMs with a resolution of 10 meters and more. In the last ten years LiDAR systems and DTM filter techniques have improved so far that operational, reliable tools for the generation of DTMs with a resolution of 5 meters and less are available today. As LiDAR can penetrate the canopy of high vegetation highly accurate DTMs can be derived even for forested areas (Pfeifer and Kraus 1998). With the growing availability of high resolution DTMs from airborne LiDAR, input for medium and fine-scale applications can be improved significantly.

2. Aims and Methodology

2.1 Scope of Work

The aim of the present study is to identify landform elements which relate to specific conditions for soil formation and are referred to as soil-landform entities in this paper (MacMillan et al. 2000). As most pixel-based algorithms for the detection of landforms were developed for coarser DTMs, the applicability of these approaches on high resolution LiDAR DTMs is limited (Wood 1996). The most substantial difficulties arise from (a) the strongly varying scales of the demanded landform elements ranging from only a few metres to several kilometres, (b) random errors in the DTM (“noise”), which makes it difficult to distinguish significant changes in the relief from unwanted artefacts and (c) minor anthropogenic modifications of the relief, e.g. terraced fields or drainage channels. Instead of using a pixel-based approach, the concept of object-based image analysis (OBIA) as a new tool for morphometric analysis (e.g., Drăguț and Blaschke 2006) is applied. Derivatives of LiDAR DTMs are used as input for an OBIA-workflow that is implemented in a selected test area. Significant soil-landform entities are delineated and classified.

Classification results are compared to soil-landform entities derived from a coarser photogrammetric DTM. Benefits of airborne LiDAR DTMs for this procedure are exemplified.

2.2 Study Area and Basic Data

The study area presented in this paper is located around the city of Bruneck (Italy). It covers approximately 75 km² and has an altitudinal range from 748 to 2,276 m. The main focus is on the area below 1,000 m a.s.l. representing the basin of Bruneck. It is mainly formed by alluvial fans, flood plains and terraces of the rivers Ahrn and Rienz, and isolated outcrops of metamorphic bedrock (phyllite, schist). A LiDAR DTM (2.5 m cell size) and a photogrammetric DTM (20 m cell size) are used along with a land use map (1:10,000).

2.3 Methods

Fig. 1 shows the workflow used to develop a map of soil-landform entities from a LiDAR DTM applying an OBIA approach. The same procedure is carried out with a photogrammetric DTM to compare the results. Data on land cover is merely used to mask out rivers and areas where relief and soil formation is distorted significantly by anthropogenic influence (settlement areas, roads).

Input data for the OBIA are various terrain parameters that are derived in a first step with existing GIS-algorithms (Fig. 1, section 2). In addition to standard terrain derivatives, complex parameters are determined to detect landform elements in a heterogeneous environment. The “vertical distance to channel network” (VDCN, Bock and Koethe 2008) is adjusted and calculated separately for each watershed.

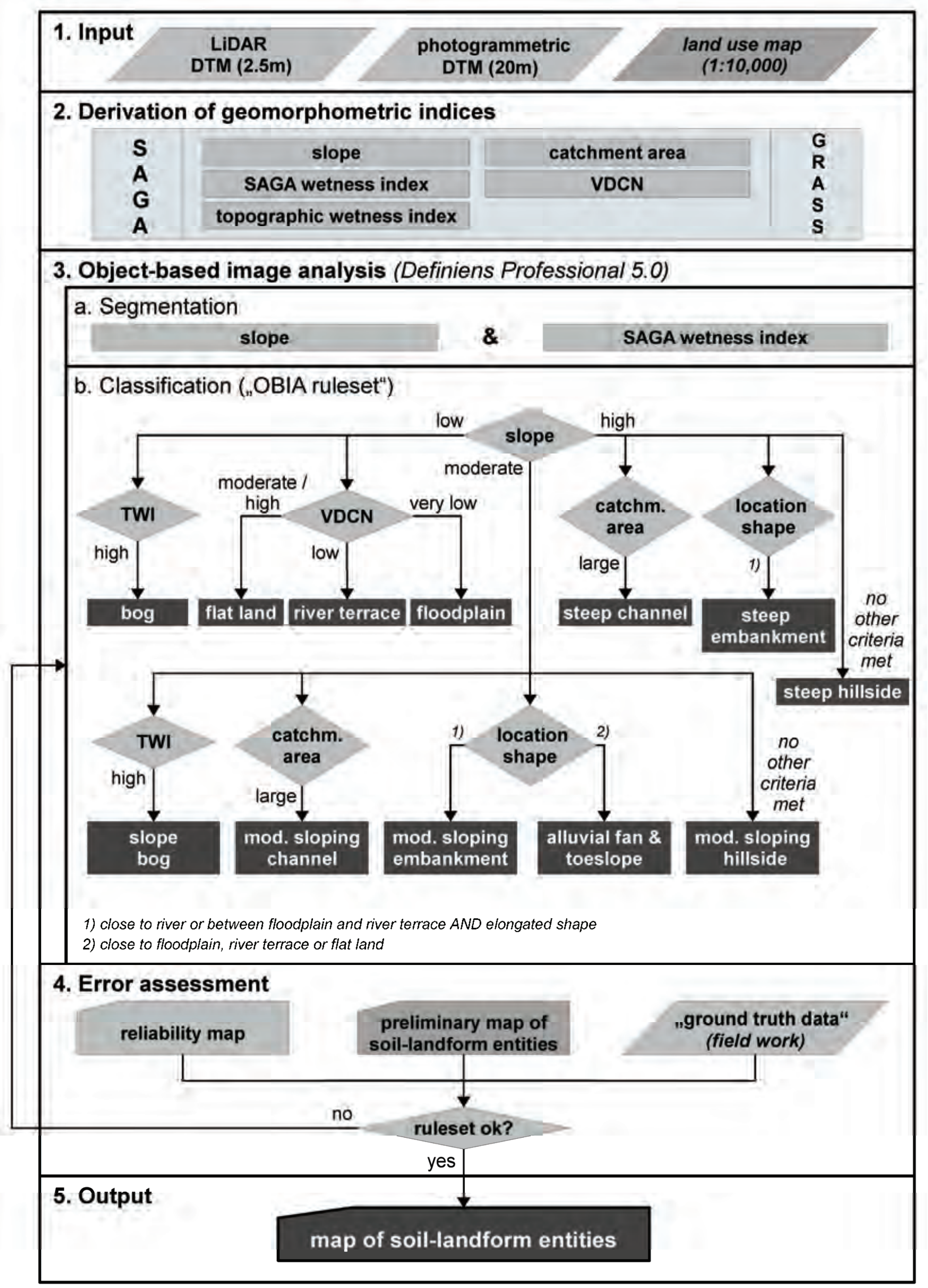


Figure 1. Workflow of the OBIA for Bruneck.

In a next step, OBIA is carried out applying an expert-driven semi-automated approach for the segmentation and classification process (van Asselen and Seijmonsbergen 2006, Schneevoigt et al. 2008). Multi-resolution segmentations based on the equally weighted parameters slope and SAGA wetness index (Boehner et al. 2002) are used to create a hierarchical segmentation with an increasing level of detail by decreasing the scale parameter (Baatz and Schäpe 2000). The compound terrain parameter SAGA wetness index proved to return better results than the basic terrain parameter catchment area, due to its capability of smoothing out small variations in flat areas (Böhner et al. 2002). The scale parameters used for the LiDAR DTM (10 on the highest level of detail) and the photogrammetric DTM (2) have to be chosen independently to guarantee segments of comparable size. Measures of curvature were integrated in the segmentation process first, but did not improve results due to a high sensitivity to the problems mentioned above (chapter 2.1) and are not used in this approach.

For the classification, a set of rules based on expert knowledge is developed to describe the relevant soil-landform entities (Fig. 1, section 3b). Instead of strict threshold values fuzzy classifiers are used to capture characteristics of the relief as a gradually alternating object. In a first classification step areas with similar slope processes are detected using the fuzzy membership function shown in Fig. 2. This first allocation reflects the distinctive gravitational influence of the relief on soil formation in a mountainous environment. Our choice of fuzzy membership functions is based on Schneevoigt et al. (2008) and observations from field work prior to the elaboration of the rule set.

In a second classification step river terraces and floodplains are separated from other objects with shallow slopes by their vertical proximity to a major river. Embankments are defined as objects of elongated shape, steep slope and adjacency to a river terrace or a floodplain. Hillside objects are distinguished from alluvial fans and areas at the bottom of slopes (toeslope) by analysing whether an adjoining object is classified as flat land, floodplain or river terrace. Other landform elements are identified according to the parameters shown in Fig. 1.

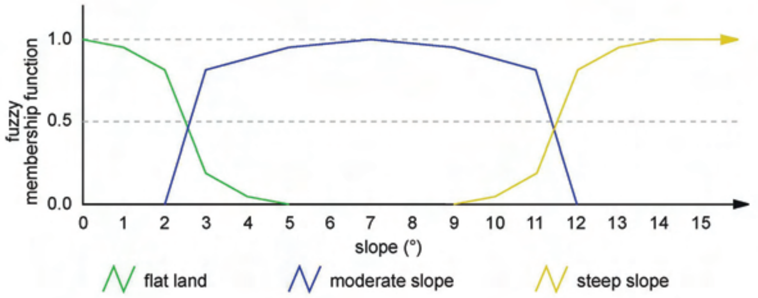


Figure 2. Fuzzy membership function of “slope” for the first classification step.

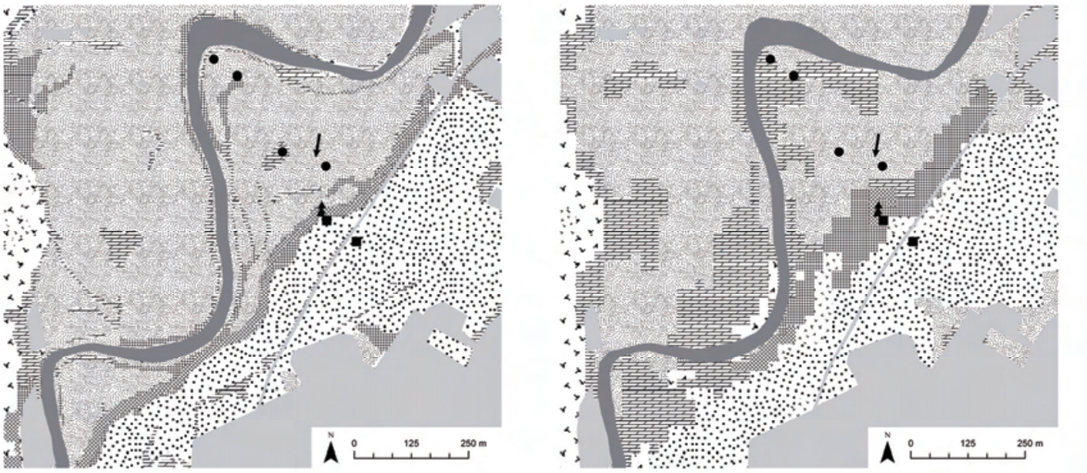
3. Results

The final outcome is a map of landscape elements including both geomorphic and hydromorphic features (Fig. 3a and b). It is intended to assist the field work for fine-scale soil mapping and to provide an input for subsequent digital soil mapping algorithms. Rather than geomorphologic units the map shows a classification of terrain in view of different conditions for soil formation (soil-landform entities).

Tab. 1 (split in two parts for lack of space) summarizes a first quality assessment of the OBIA classification. The columns show which percentage of the area assigned to each class derived from the LiDAR DTM is covered by each class derived from the photogrammetric DTM. Entities that cover large areas, such as steep hillside slopes and alluvial fans & toeslopes are congruent to a high degree. Entities of limited extent in at least one direction (e.g., embankments) are identified poorly. Small soil-landform entities based on hydrologic features (bogs) are excluded from this comparison since no meaningful representation is possible from the photogrammetric DTM.

		Classification of LiDAR DTM (2.5m)								
	class	flood plain	river terrace	flat land (unspecified)	alluvial fan & toeslope	steep hillside	mod. slop. hillside	moderate embankm.	steep embankm.	unclassif.
Classification of photogrammetric DTM (20m)	flood plain	**58,81**	11,78	1,13	1,16	0,06	0,02	17,64	7,03	0,00
	river terrace	3,06	**55,60**	10,18	2,36	0,02	0,00	7,72	1,60	0,00
	flat land (unspecified)	0,00	0,11	**37,12**	2,85	0,07	0,17	0,02	0,21	0,00
	alluvial fan & toeslope	26,47	23,19	42,80	**75,57**	2,67	2,85	49,37	32,24	40,89
	steep hillside	1,08	0,57	1,83	11,85	**91,95**	47,80	6,96	35,22	49,77
	mod. sloping hillside	0,43	2,28	2,60	4,50	5,17	**48,61**	1,50	2,74	9,34
	moderate embankment	4,12	4,01	0,12	1,03	0,04	0,03	**13,39**	15,93	0,00
	steep embankment	0,13	0,20	0,00	0,06	0,01	0,00	1,42	**3,48**	0,00
	unclassified	5,90	2,26	4,24	0,62	0,02	0,53	1,99	1,55	**0,00**

Table 1. Comparison of landform classification of LiDAR DTM and photogrammetric DTM (%).



(a) Landform classification of LiDAR DTM

(b) Landform classification of photogrammetric DTM

(c) Orthophoto

(d) Photo from field work

Figure 3. Comparison of landform classification of (a) LiDAR DTM and (b) photogrammetric DTM with orthophoto (c) and field photo of flood plain and embankment (d).

Further error assessment is made by comparing field data to the results of both classifications. More than 260 soil profiles were sampled with a Pürckhauer auger and the associated landform was recorded. Fig. 3a and b show the results of both classifications for a small section of the river Ahr and adjacent flood plains, river terraces and embankments as well as the location of seven soil profiles. The comparison to the same section in the orthophoto (Fig. 3c) shows that a correct classification under forest canopy is only possible by using the LiDAR DTM as an input. The poor classification of embankments using the photogrammetric DTM can also be observed by comparing Fig. 3a and 3b to the field work data (location of soil profiles and Fig. 3d).

4. Conclusions and Future Work

The presented study shows the potential of LiDAR data for geomorphometric analysis as input for soil mapping. A method to detect homogeneous areas, in terms of unique conditions for soil formation, from secondary data sources shall reduce time consuming field work to a minimum. However, for highly populated, mountainous regions, it is obvious that an automatically derived map from terrain parameters and land use data cannot fully replace but at least assist conventional soil mapping (Friedrich 1996). Verification of soil-landform delineations in the field will always be necessary.

More sophisticated ground truth data using differential GPS will be collected. Specific landform entities and topographic profiles will be surveyed to determine the spatial accuracy of the results derived from the LiDAR DTM. An error assessment will be made by comparing mapped landform entities to classification results as shown in Table 1. Finally the transferability of the approach will be tested by comparing the results obtained in this study to the results from a second test area in the Inn Valley (Kramsach, Austria) with different topographic conditions.

Results will also be integrated in a digital soil mapping approach using classification and regression trees to derive comprehensive conceptual soil maps for the investigation areas. Soil classes and specific soil properties will be assessed and are used for an evaluation of natural soil functions as additional input for spatial planning procedures.

Other fields of application include the research on soil formation processes in Alpine areas. A special focus is set on the influence of relief on various scales and the investigation of hydraulic properties of soils to determine the relevance of soil for the development of storm water runoff in Alpine catchments.

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