A Revolution in Geomorphology

Terrain analysis in geomorphology has undergone a serious quantitative revolution over recent decades. Lidar information has been efficiently used to automatically classify discrete landforms, map forest structures, and provide input for models simulating landscape development, e.g. channel incision development and rock-fall processes. Quantitative digital terrain analyses and dynamic modelling in geomorphology and forestry have immensely increased the validity of future landscape change scenarios. Further developments in digital GIS-based maps may lead to standardised automated terrain-analysis techniques and more insight into landscape evolution.<P>

Terrain analysis has for decades been the domain of experienced earth scientists. Before the introduction to geomorphology of computational models and simulations, landscape analysis was time-consuming and difficult to perform whenever it involved inaccessible and/or forested terrain. Current developments in automated terrain analysis are based on statistical geomorphometrical concepts and use Digital Terrain Models (DTMs). As stated by Pike in his 2008 chapter in Geomorphometry: Concepts, Software, Applications. Developments in Soil Science (to be published shortly), 'Geomorphometry combines geosciences, mathematics and computer science for land surface analysis and assumes that a relation exists between surface processes and surface morphology'. Examples covered in this paper illustrate current and future research by the computational geo-ecology department of the University of Amsterdam.

Geometric Signatures

Wood stated in 1996 that digital elevation models (DEMs) were frequently used to extract elevation derivatives such as slope angle, plan and profile curvature, aspect, local drainage direction and up-slope area. We see that a common concept in DEM-based landform mapping is that each discrete landform type has a characteristic combination of elevation derivatives, i.e. a geometric signature. This means that automatically Lidar-extracted 'terrain objects' or 'segments' contain 'unique' statistical information representative of that specific landform type. In theory, a known training set or 'geomorphometrical signature library' can be used to compare extracted terrain objects with standard 'discrete landform' examples for automatic as such classification. In reality, however, younger surface processes may (partly) transform discrete terrain forms into other landforms, e.g. a glacial landform stemming from the last glacial period may be transformed by post-glacial mass movement. This implies that the statistical information of such landforms may also be 'inherited' from an earlier landform. Fuzzy membership classification methods are used to overcome this problem, and objects classified as belonging to more than one class. Ultimately this may lead to a digital geomorphological map linked to a spatial geodatabase in a GIS, as proposed by Gustavsson, Seijmonsbergen and Kolstrup.

Landform Mapping

A test was carried out in the European Alps to automatically map discrete landforms like glacial landforms, alluvial fans, fluvial terraces, incised channels, rock cliffs, talus slopes and landslide units using slope angle and altitude from 1m-resolution Lidar data. The method used is outlined in Figure 2; here a 1:10,000-scale geomorphological map provides the source for delineating geomorphological units in a GIS (step 1). Zonal statistical information for each terrain unit is taken from the corresponding Lidar data (step 2). This information is used to compare automatically derived segments from Lidar elevation and slope angle data (step 3), classified (step 4) using the statistics of step 2. Comparison of the results (step 5) allows classification of other areas. Accuracies of 79% for alluvial fans, 70% for deeply incised channels, 69% for fluvial terraces, 63.5% for talus slopes and 61% for glacial landforms were calculated. Mass movement (50%), rock cliffs (32%) and shallow channels (23%) performed less well. The inclusion of additional statistical information such as aspect, convexity and concavity is expected to increase accuracies.

Mapping Forest Structure

Not only landform type, but also the vegetation may be crucial in the functioning and management of geo-ecological systems. For example, forest structure plays a vital role in the capacity of a mountain forest to protect itself against natural hazard. New methods for documenting temporal change in forests are developed through the automatic extraction of forest-stand information from Lidar DEMs. Individual tree crowns were calculated by subtracting the digital terrain model (DTM) from the digital surface model (DSM). The resulting Canopy Height Model (CHM) was used to determine individual forest-stand objects using multi-resolution segmentation with the eCognition software (Definiens Imaging). The forest stands were further analysed using local maxima techniques to locate individual treetops, and were classified into four categories (<3m, 3-8m, 8-20m and >20m). To validate the results, the method was compared with detailed 0.5m-resolution false-colour infrared orthophotos and field visits to various forest stands. Statistical indices (Shannon Evenness Index and a modified Division Index) were calculated to analyse tree-height diversity and openness of forest stands. This information served as parameter input for the classification of forest stands into six discrete structures: young growth, open forest, multi-layered dense forest, multi-layered open forest, uniform dense forest and uniform open forest.

Aboveground Biomass

Tree height values can also serve as input for allometric equations, allowing estimation of the Diameter at Breast Height (DBH) of individual trees. The relationship that exists between DBH and aboveground biomass is dependent on tree species (in this case the dominant species was Norway Spruce). Figure 3 shows an example of forest stands with calculated biomass values for each stand. The same process may also be automated and allows foresters to easily evaluate the growing stages of a forest. It is moreover possible to rapidly assess carbon stock at catchment or country scale for the evaluation of, for example, agreements set down in the Kyoto Protocol.

Applying Lidar

Lidar data was recently applied to a geomorphological study of landscape evolution in complex alpine terrain using a simulation model. The aim of this data was (1) to analyse morphological distribution of present landscape, (2) to reconstruct late-glacial hill-slope geometry, and (3) automatically locate river channels based on local drainage direction as calculated from the altimetry data. This information served as initial conditions for a dynamic model simulating post-glacial landscape evolution. A vector channel incision model (CIM) calculates the vertical incision rates of mountain rivers into bedrock, based on channel discharge, gradient, geological resistance against erosion and lack of channel equilibrium. The CIM is combined with a gridcell-based erosion model to simulate hill-slope evolution as a response to fluvial erosion. Model performance was evaluated by comparing the calculated cross-section and longitudinal profiles with those extracted from the Lidar imagery. Future implementation of discrete landform and forestry mapping in dynamic geomorphological simulation models may lead to a better understanding of mountain landscape dynamics. This might be used to evaluate potential natural hazard or risk to population and infrastructure, and to better predict the effects of change in land use or management.

Concluding Remarks

The use of high-resolution Lidar data in terrain analysis has definitely opened up new potential in landscape mapping, forestry applications and dynamic landscape simulation modelling. The conclusions may be summarised as follows:
- more precise delineation of landscape terrain boundaries and more repeatable statistical methods
- Lidar information yields better recognition and interpretation of landform and processes, especially under forest cover
- combining Lidar-based statistical information and high-resolution orthophotos improves efficiency and time spent on fieldwork
- increased insight into functioning of geo-ecological systems will result from new multidisciplinary approaches using modelling, GIS and remote sensing.

We foresee that disadvantages such as cost and the fact that Lidar data is not widely available, and specific requirements relating to soft- and hardware, will be reduced over coming years. In particular, the monitoring of landform and land-cover change using multi-temporal high-resolution Lidar datasets will further enhance terrain analysis research.

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Further Reading

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