DIGITAL GEOMORPHOLOGICAL INFORMATION FOR ALPINE HAZARD STUDIES USING LASER ALTIMETRY DATA AND GIS

WITH AN EXAMPLE FROM VORARLBERG, AUSTRIA

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SUMMARY

Detailed geomorphological information has proven beneficial for the spatial recognition and delineation of natural hazards such as rock fall, slides and debris flows in alpine ecosystems. New digital (semi-)automated mapping and availability of LiDAR altimetry data may improve the accessibility and accuracy of detailed geomorphological information, which can be used as input in hazard studies. A first improvement is that digital geomorphological maps store both terrain units and attributes which describe color coded landforms, processes and deposits. These terrain units are categorized using a morphogenetic classification scheme to preserve most information displayed in traditional paper geomorphological map. A second improvement is the (semi-) automated extraction of statistical morphometric information derived from digital elevation models, which can be related to the digital landform units recognized in the digital geomorphological map. Existing techniques used for the extraction of geometrical derivatives only focused on deriving slope angle, curvature, altitude and aspect and mostly in homogeneous terrain and not on genetic and process information. High resolution laser altimetry data makes statistical separation of terrain objects derived from LidAR DEMs possible. First results show that integration of expert knowledge rules makes it possible to classify and group individual objects into unique geomorphological terrain units that are related to the *genesis* of landforms. These two parallel developments result in new information that serves as input in alpine hazard zonation studies. In this study a method for the preparation of digital geomorphological maps in Vorarlberg is presented and it is shown how simple landscape metrics can be used in the semi-automated recognition and classification of geomorphological information from LiDAR information. The methods include digital geomorphological GIS map preparation and visualization using a standardized morphogenetic classification scheme and object oriented classification of a LiDAR dataset combined with zonal statistical analysis in a GIS environment. Direct advantage and improvements over existing methods are improved understanding of landscape process in inaccessible and/or forested areas, increase in mapping accuracy and improved consistency in the objectivity and reproducibility of the mapping methods. Moreover, expert knowledge rules can be added to this process. The resulting information can serve as input into hazard zonation studies and be displayed either as a 'flat' computer screen map in GIS, as a paper map, a "bird's eye view" or alternatively, as an overlay in 'Google Earth'.

Keywords: Geomorphological mapping, Natural Hazards, GIS, LiDAR

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INTRODUCTION

Geomorphological maps are a traditional source for the archiving of landscape information. An ideal geomorphological map should contain information on morphometry, materials, processes and genesis (Klimaszevski, 1982, Barsch et al. 1987, Gustavvson et al., 2006). Such maps have formed the basis for natural hazard and risk assessment on various scales (Seijmonsbergen 1992, Seijmonsbergen and De Graaff 2006). The last decade, digital terrain models (DTM's) supply new and additional information to the battery of available statistical techniques in hazard studies (Giles et al. 1998, Miliaresis and Argialas, 2002). Techniques such as heuristic, deterministic and statistical landslide analysis (Guzetti et al. 1999, Soeters and van Westen 1996, Van Westen 2000, Moon and Blackstock 2004) all depend on the availability of (often inaccurate and low resolution) digital elevation data, digitized manually from contour line maps or through the processing of stereo air-photos or satellite imagery. This study aims at the improvement of experience-driven hazard zonation in alpine areas by combining digital geomorphological mapping and 1m resolution laser altimetry data (LiDAR). Further development of methods for the extraction of terrain variables from laser altimetry data (LiDAR) will result in semi-automated classification methods that will integrate laser altimetry datasets for the recognition of processes and landforms in alpine geo-ecosystems (see also Van Asselen and Seijmonsbergen, 2006). A total of 750 square kilometer of the geomorphology in Vorarlberg has been mapped at scale 1:10.000, using a traditional symbol-based mapping method. Recently, the University of Amsterdam in cooperation with the Research Foundation for Alpine and Subalpine Environments (RFASE) and the Nature museum 'inatura' have initiated a digital mapping inventory, which will lead to implementation of digital geomorphological maps in the local GIS system of Vorarlberg (VOGIS). Parallel to this development, newly available data, such as laser altimetry data at 1m resolution and digital false color ortho-photo's, are tested for the automated recognition, delineation and visualization of processes and landforms in a GIS environment. In combination with the calculation of zonal statistics, calculated from segmented LiDAR data, a geodatabase is used from which a hazard zonation map can be prepared using relatively simple GIS analysis in which expert-knowledge rules and automated zonal statistical techniques are combined. The value of the traditional geomorphological paper maps is that they serve as valuable documents for accuracy assessment evaluation and landscape interpretation in general. In the next decade laser altimetry terrain and surface models will become the new standard for the major part of the earth surface, most likely fed by satellite based temporal high resolution altimetry datasets. Therefore this study seeks to develop, explore and implement new scientifically sound methods that can improve current hazard assessment analyses.

AREA DESCRIPTION, GEOMORPHOLOGY AND SEMI-AUTOMATED MAPPING

Digital geomorphological mapping and area description

The digital geomorphological map example of the Gamp Valley in the Rätikon Mountains in Vorarlberg is an excerpt of an existing paper 1:10.000 scale geomorphological symbol map (Seijmonsbergen, 1992), and based on a legend for alpine areas described by De Graaff et al. (1987). For this study, the map was digitized and labeled using a standardized morphostratigraphic legend (Seijmonsbergen et al. in press) which is partly shown in table 1. This legend can also be used in direct digital field mapping in combination with mobile GIS for collecting relevant attributes determined in the field. Geomorphological processes and 'landforms and deposits' in this digital legend form the basis for delineating basic landforms

which include hazard polygons. Tests show that the use of LiDAR data as transparent backdrop imagery to aerial photographs and topographical base maps improves the delineation of landforms boundaries, especially in forested and/or inaccessible areas.
The geomorphology in the study area shows a variety of landforms, which include glacial landforms (cirques, hanging valleys, moraine deposits), landslides (rockfall, debris flows, solifluction processes, deep seated slope failures), karst landforms (surface solution, collapse dolines, cementation) and fluvial landforms and deposits (river terraces, river incisions, alluvial fans, gullies).

Tab. 1: Short version of the digital geomorphological legend and corresponding GIS codes (after Seijmonsbergen et al. in press).

Processes			**Landforms and deposits**	**GIS code**
Glacial (1000)	Erosion (1100)	1110	Glacially eroded bedrock	1111
			Glacially eroded Quaternary deposits	1112
	Accumulation (1200)	Subglacial (1210)	Landforms underlain by subglacial till s.l.	1211
		Ice Marginal (1220)	Landforms underlain by ablation till s.l.	1221
			Erosional landform	1222
			Landform underlain by fluvial deposits	1223
			Landform underlain by lake fill deposits	1224
Fluvial (2000)	Erosion (2100)	(2110)	Incision: slope subject to fluvial erosion	2111
	Accumulation (2200)	(2210)	Recent streambed	2211
			Fluvial terrace	2212
			Alluvial fan, debris fan	2213
			Landform underlain by lake fill deposits	2214
Mass Movement (3000)	Degradation (3100)	(3110)	Slope with deep seated mass movement	3111
			Slope with shallow mass movement	3112
	Accumulation (3200)	(3210)	Landforms underlain by fall deposits	3211
			Landforms underlain by flow and/or slide deposits	3212
Periglacial (4000)	Disintegration (4100)	(4110)	Terrain subject to disintegration	4111
	Accumulation (4200)	(4120)	Rock glacier	4211
Organic (5000)	(5100)	(5110)	Landform underlain by peat deposits	5111
Karst (6000)	Carbonate karst (6100)	(6110)	Slope surface strongly affected by carbonate karst	6111
	Sulphate Karst (6200)	(6210)	Slope surface affected by gypsum karst	6211
Aeolian (7000)	Accumulation (7100)	(7110)	Landforms underlain by aeolian deposits	7111
Human (8000)	(8100)	(8110)	Graded or leveled land	8111
			Pits, quarries	8112
Water (9000)	(9100)	(9110)	River	9111
			Lake	9112

Cross sections through the upper Gampbach Valley (fig. 2) show the relations between process, slope angle and geology. The presence of gypsum (part of Raibler Formation) in the subsurface leads to a series of karst related landforms and processes, e.g. collapse karst, naked and covered karst and to fixation of Pleistocene sediments (see also Cammeraat et al. 1987). A striking example of an active deep-reaching landslide is shown in figure 1 left, photo.

Subsurface dissolution of gypsum initiated detachment and collapse/subsidence of this large dolomite rock slab, schematically represented in the cross section of fig. 2A. Accompanying rock fall and debris flows partially filled the naked gypsum karst depressions (example on right hand photo in fig. 1). Thematic maps are displayed in figure 4 together with corresponding LiDAR and false color infrared data.

Fig. 1 Photo left: Back and side scarp of active deep reaching landslide in the Upper Gamp Valley, which was initiated by subsurface gypsum dissolution (see also fig. 2) Photo right: Debris flow partially trapped in a covered gypsum karst depression (lower foreground).

Semi-automatic mapping and classification using expert rules

High resolution Digital Terrain Models (DTM) and Digital Surface Models (DSM) can be generated by LiDAR data (Light Detection And Ranging), because part of the laser beams penetrate the vegetation cover and is reflected on the terrain surface (Clark et al. 2004, Hyyppa et al. 2004). This provides detailed morphometrical information of both forested and poorly accessible terrain. The strength of the new technique is the resolution: 1m resolution DEMs lie well within the detection limits of individual landforms. Until now, only selected geometrical derivatives of DEM data has been used to identify geomorphological features such as landslide scars, glacial erosion and floodplain geomorphology (Charlton et al., 2003, Hooper et al., 2003, Adediran et al., 2004, McKean and Roering 2004). Because of the fine landscape fragmentation in the Alps, laser altimetry data is highly suitable for analysis using object oriented analysis techniques. This technique uses multiple information for the classification of image objects, and is not restricted to 'per pixel' classifications (Benz et al., 2004). It is especially recommended for analyses of high resolution images (Hoffmann and Vegt, 2001; Schwarz et al., 2001; Kayakire et al., 2002) and was recently tested on a laser DEM (Asselen van, and Seijmonsbergen, 2006). The resulting objects are created in a user steered segmentation process, and potentially contain information which is used for statistical analysis and terrain classification. The units recognized should match the landforms present and processes acting in the terrain and thus reflect genetic units. Statistical information of slope angle and elevation is then compared to digital geomorphological polygons. Since many alpine landforms show inherited characteristics of landforms and processes related to former glacial periods, they can be regarded as *fuzzy land units* and as such the resulting classes can be expressed in terms of membership values (Burrough et al., 2000), which is common in object oriented classification techniques. The resulting categories are based on the highest membership values.

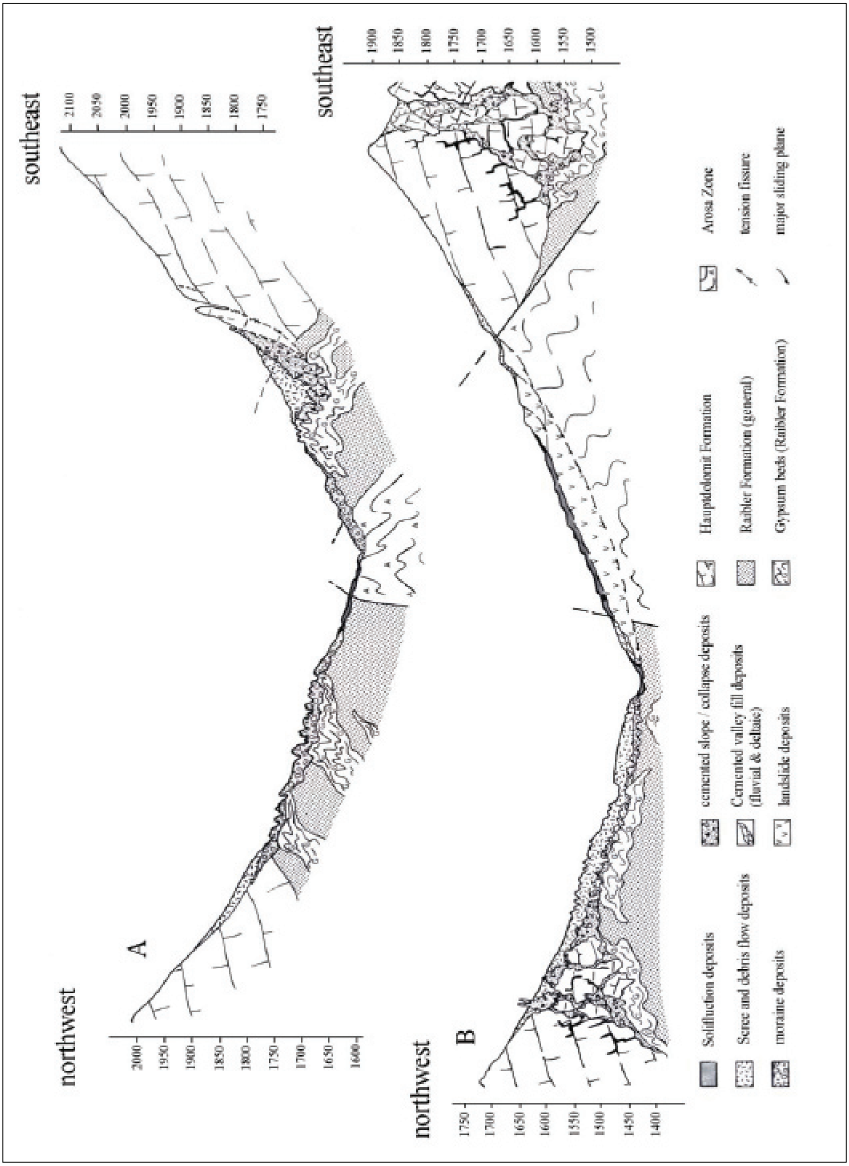
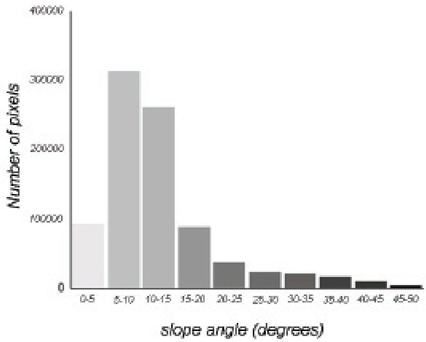


Fig. 2 Two cross sections through the upper Gampbach Valley, illustrating slope collapse in dolomite limestone initiated by gypsum dissolution in the subsurface and development of bedrock subsidence, naked and covered karst and cementation of Pleistocene deposits leading to relief inversion after deglaciation (after Seijmonsbergen, 1992).

Many landforms have distinct shapes, e.g. an alluvial fan is conical, a valley floor slopes with the river, river terraces are elevated above and slope with the river, a deep incision shows opposite slope aspects and a rock fall scree slope is located below a steep cliff, and is characterized by slope angles near the angle of repose. Undisturbed, fully intact landforms can thus be characterized by the frequency and/or association of topographical attributes, e.g. a conical shaped alluvial fan has fewer pixels in the high elevation range if compared to the lower elevation range. An example of frequency histograms for an alluvial fan in the study area is given in fig. 3. For each landform such expert knowledge rules were formulated. This geomorphological expert knowledge is used in the classification process by using zonal statistical analyses and the introduction of thresholds, e.g. scree cones have slope angles between 28-35 degrees. In this way, the statistics can be compared to standard 'ideal' landforms. In practice however, most landforms will miss certain parts, because of younger erosion or degradation processes. In this study, expert rules based on altitude and slope angle have been made for the common landforms. These were tested against terrain units digitized from the paper geomorphological map.



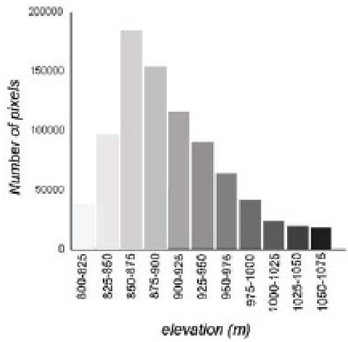


Fig. 3 Characteristic examples of the frequency distribution for slope angle (left) and elevation (right) for pixels within an alluvial fan in the study area, calculated using zonal statistics from the LiDAR data and based on the fan polygon boundary.

RESULTS

The first two digital A1-sized 1:10.000 geomorphological maps have been finished. In a GIS environment the resulting color coded digital geomorphological map can be displayed with the traditional symbol based geomorphological map as a backdrop image (fig. 4a - bottom). The linked attribute table contains information on hazard type (conform table 1) and process activity, which is categorized into three classes, R = red (active) zone, G = yellow (medium active) zone and N = green (low activity) zone (fig. 5, right). Further attributes on slope angle and altitude per land unit (see fig. 5) were imported from zonal statistical analysis, based on the LiDAR DEM. The GIS environment also allows to actually fly through the database simulating a 'bird's eye' view using LiDAR data resolution, which enables visual validation and evaluation which may lead to updates of the geodatabase. In fact, the final digital geomorphological map

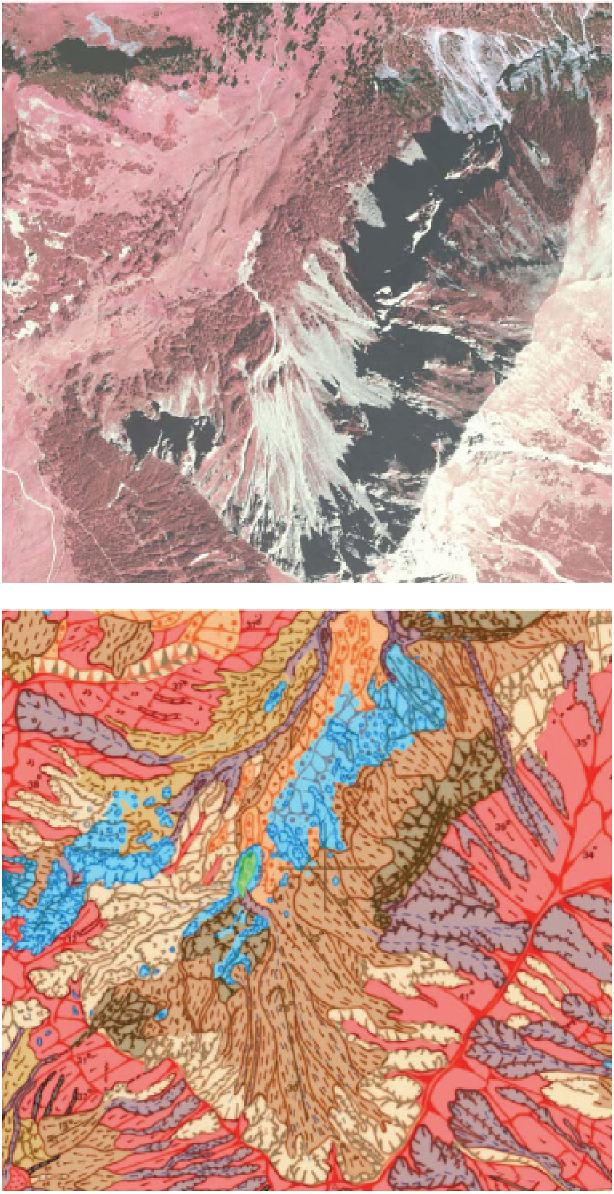


Fig. 4a Top: False Color 50 cm resolution infrared ortho-photo. Bottom: Part of the color coded digital geomorphological map and the scanned paper geomorphology map as a backdrop image. See also figure 4b, next page.

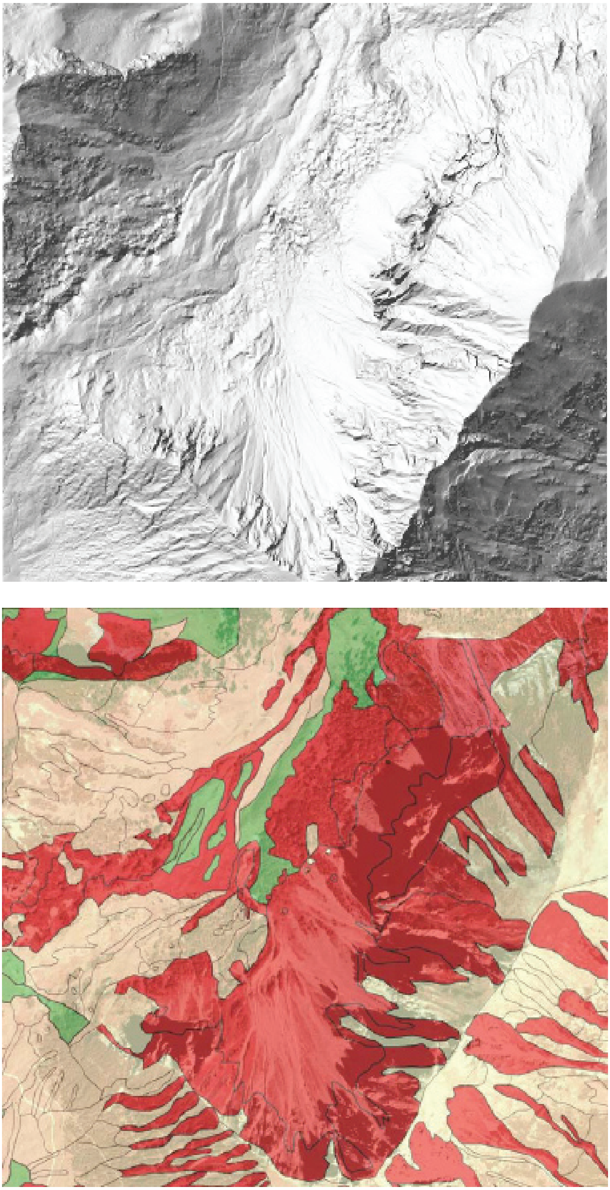


Fig. 4b Top: 1m resolution LiDAR shaded digital elevation model. Bottom: Hazard zonation map based on expert knowledge rules and LiDAR information. It displays basic polygon hazard boundaries and the false color infrared air photo as a backdrop image: Red (active) zone, Yellow (medium activity) zone and Green (low activity) zone.

was finalized by on screen comparing the boundaries of the scanned original paper map with the potential boundaries from the LiDAR data. In some cases minor changes to boundaries (not interpretations) were made by this visual assessment, while most deviations occurred in steep, forested areas. The results of zonal statistical analysis for various landforms are calculated for the geomorphological map sheet St.Gallenkich (Seijmonsbergen, 1996) in Montafon, southeast Vorarlberg (compare van Asselen and Seijmonsbergen, 2006). The first outcomes are promising (fig. 5). In general, the fluvial (alluvial fan, terraces, incisions) and glacial landforms can be separated quite satisfactory, the mass movement related landforms other than rock cliffs and rock fall deposits, show less evident relations, and partially overlap with glacial landforms. This can be explained by the fact that most mass movement landforms (slide and flow) occur along a wide altitudinal range and form often irregular detailed morphology, which is characterized by rapid changes in slope angle. Their polygenetic origin is another confusing factor.

CONCLUSIONS AND DISCUSSION

The combination of digital geomorphological maps and LiDAR data may have the following benefits for alpine hazard zonation studies. (1) existing geomorphological maps can be re-evaluated and improved during conversion into digital maps which increases accuracy of land unit boundaries (2) zonal statistical analysis of LiDAR data based on digital geomorphological polygons adds specific statistical morphometrical signatures to the digital geomorphological map (3) integration of expert knowledge rules in automated classification of LiDAR data will lead to more consistent and objective documentation of geomorphological information and (4) alpine hazard assessment studies may benefit from the improved statistical and geomorphological information offered by the combination of digital geomorphological maps and LiDAR data.

It is foreseen that integration of additional LiDAR DEM derived variables, such as aspect, upslope areas, curvature etc. will lead to even better classification of landforms and processes, which will undoubtedly improve basic hazard zonation boundaries. It is tentatively foreseen that the relative activity of processes can be extracted from LiDAR data. Initially, active landslides produce ‘sharp’ morphology. This morphology will be ‘wiped out’ over time, after levelling by younger processes. The statistical signature will change accordingly. This means that fresh and old units can potentially be separated and that polycyclic landforms, which are common phenomena in the Alps, may show a mixed signature.

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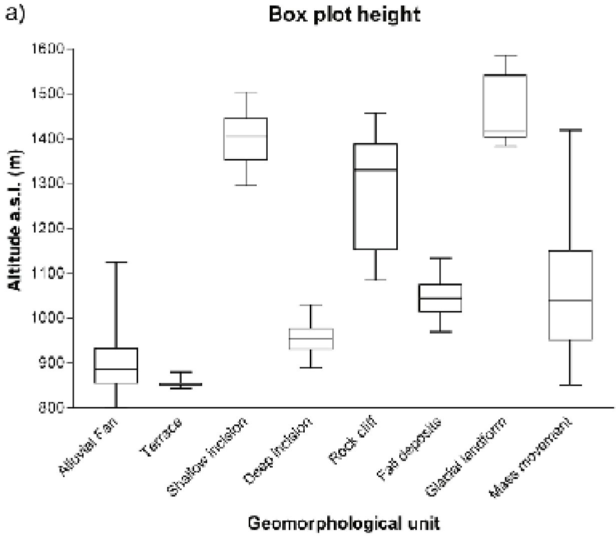

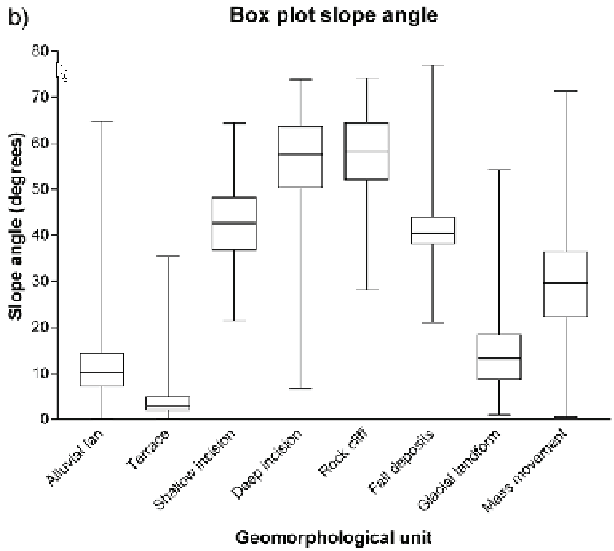

Fig. 5 Box plots of selected geomorphological units versus altitude range (a) and slope angle (b) (after van Asselen and Seijmonsbergen, 2006).

LITERATURE

Adediran, A.O., Parcharidis, I., Poscolieri, M., Pavlopoulos, K., (2004):„Computer-assisted discrimination of morphological units on north-central Crete (Greece) by applying multivariate statistics to local relief gradients". Geomorphology 58, 357-370

Asselen van, S., Seijmonsbergen, A.C. (2006): „Expert driven semi-automated geomorphological mapping for a mountainous area using a laser DTM". Geomorphology 78, 3-4, 309-320.

Benz, U.C., Hofmann, P., Willhauck, G., Lingenfelder, I., Heynen, M., (2004): „Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information". ISPRS Journal of Photogrammetry & Remote Sensing 58, 239-258.Baatz, M. and Schäpe, A., 2000. Multiresolution segmentation – an optimization approach for high quality multi-scale image segmentation. In: Strobl L, J. et al. (eds.): Angewandte Geographische Informationsverarbeitung XII. Wichmann, Heidelberg: 12–23.

Barsch, D., Fischer, K., Stäblein, G. (1987): „Geomorphological mapping of high mountain relief, Federal Republic of Germany (with geomorphology map of Königsee, scale 1:25 000)". Mountain Research and Development 7, 4, 361-374.

Burnett, C., Blaschke, T., (2003): „A multi-scale segmentation/object relationship modeling methodology for landscape analysis". Ecological modeling 168, 233-249.

Burrough, P.A., Gaans, P.F.M., van, MacMillan, R.A., (2000): „High-resolution landform classification using fuzzy k-means". Fuzzy sets and systems 113, 37-52.

Cammeraat, L.H., De Graaff, L.W.S, Kwadijk, J.K., Rupke, J. (1987): „On the origin of debris pillars in the Alps of Vorarlberg, Western Austria". Zeitschrift fur Geomorphologie 31-1, 85-100.

Charlton, M.E., Large, A.R.G., Fuller, I.C., (2003): „Application of airborne lidar in river environments: the river Coquet, Northumberland, UK". Earth Surface Processes and Landforms 28, 299-306.

Clark M.L., Clark D.B., Roberts, D.A. (2004): „Small-footprint lidar estimation of sub-canopy elevation and tree height in a tropical rain forest landscape". Remote Sensing of Environment 91, 68–89.

Graaff De, L.W.S., De Jong M. G. G., Rupke, J., J. Verhofstad (1987): „A geomorphological mapping system at scale 1 : 10,000 for mountainous areas". Zeitschr. für Geomorph. N.F., 31-2, 229-242.

Giles, P.T., Franklin, S.E. (1998): „An automated approach to the classification of the slope units using digital data". Geomorphology 21, 3-4, 251-264.

Gustavvson, M., Kolstrup, E., Seijmonsbergen A.C. (2006): „A new symbol-and-GIS based detailed geomorphological mapping system: Renewal of a scientific discipline for understanding landscape development". Geomorphology 77, 1-2, 90-111.

Guzzetti, F., Carrara, A., Cardinali, M., Reichenbach, P. (1999): „Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy". Geomorphology 31, 181–216.

Hoffmann, A., van der Vegt, J.W. (2001): „New sensor systems and new classification methods: Laser- and Digital Camera-data meet object-oriented strategies". GeoBIT/GIS 6, 16-23.

Hooper, D.M, Bursik, M.I., Webb, F.H. (2003): „Application of high-resolution, interferometric DEMs to geomorphic studies of fault scarps, Fish Lake Valley, Nevada-California, USA". Remote Sensing of Environment 84, 2, 255-267.

Hyyppa, J., Hyyppa, H., Litkey, P., Yu, X., Haggren, H., Ronnhom, P., Pyysalo, U., Pitkanen, J., Maltamo, M. (2004): „Algorithms and methods of airborne laser scanning for forest measurements”. ISPRS Conference – Laser Scanning for forest and landscape assessment, Freiburg, Germany, 82-89.

Kayitakire, F., Farcy, C. and Defourny, P. (2002): „IKONOS-2 imagery potential for forest stands mapping”. ForestSAT Symposium, Heriot Watt University, Edinburgh.

Klimaszevski, M. (1982): „Detailed geomorphological maps”. ITC journal 1982-3, 265-271.

McKean, J., Roering, J. (2004): „Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry”. Geomorphology 57, 3-4, 331-351.

Miliaresis, G.C., Argialas, D.P. (2002): „Quantitative representation of mountain objects extracted from the global digital elevation model (GTOPO30)”. International journal of remote sensing 23, 5, 949-964.

Moon, V., Blackstock, H. (2004): „A methodology for assessing landslide hazard using deterministic stability models”. Natural Hazards 32, 111-134.

Seijmonsbergen, A.C. (1992): „Geomorphological evolution of an Alpine area and its application to geotechnical and natural hazard appraisal in the Rätikon mountains and S. Walgau (Vorarlberg, Austria)”. Ph.D. Thesis, University of Amsterdam, Physical Geography and Soil Sciences, 109 pp.

Seijmonsbergen, A.C. (1996): „Geomorphological map sheet 1:10.000 St.Gallenkirch”. Publications of the University of Amsterdam, IBED-Physical Geography.

Seijmonsbergen, A.C., De Graaff, L.W.S. (2006): „Geomorphological mapping and geophysical profiling for the evaluation of natural hazards in an alpine catchment”. Natural Hazards and Earth System Science 6, 185-193.

Seijmonsbergen, De Jong, M.G.G., De Graaff L.W.S. (2008): „A method for the identification and assessment of significance of geomorphosites in Vorarlberg (Austria), supported by GIS”. Geografica Fisica i Dynamica Quaternaria (In print).

Schwarz, M., Steinmeier, Ch., Waser, L. (2001): „Detection of storm losses in alpine forest areas by different methodic approaches using high-resolution satellite data“. Proceedings 21st EARSeL Symposium, Paris.

Soeters, R., van Westen, C.J. (1996): „Slope instability recognition, analysis and zonation. In: Turner, A.K., Schuster, R.L. (Eds.), Landslide Investigation and Mitigation, National Research Council“. Transportation Research Board Special Report 247, 129–177.

Van Westen, C.J. (2000): „The modeling of landslide hazards using GIS”. Surveys in Geophysics 21, 241-245.