Extraction and Characterisation of Landforms from Digital Elevation Models: Fiat Parsing the Elevation Field

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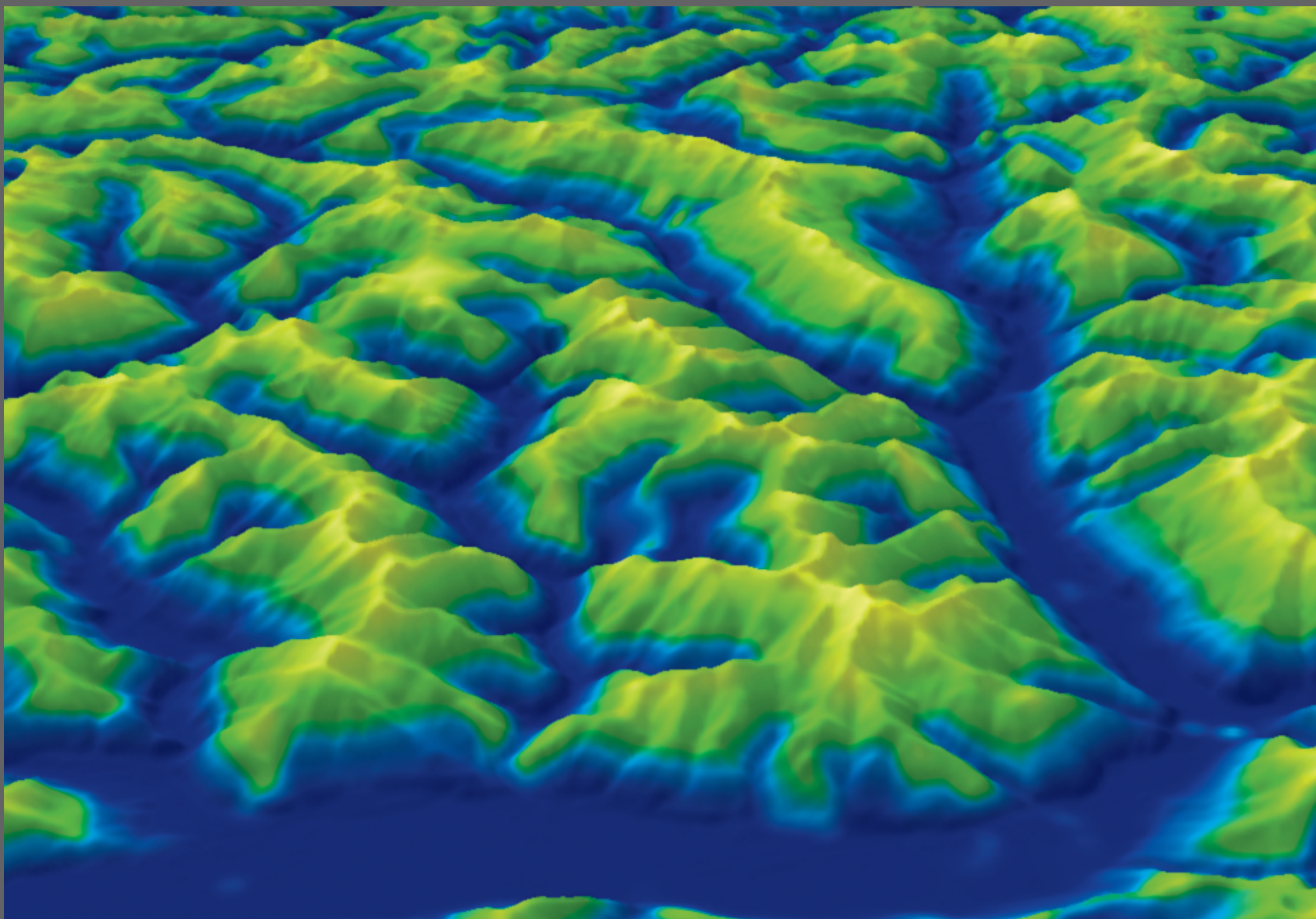

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PhD thesis
April 2010
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EXTRACTION AND CHARACTERISATION OF LANDFORMS FROM DIGITAL ELEVATION MODELS: FIAT PARSING THE ELEVATION FIELD

Dissertation
zur
Erlangung der naturwissenschaftlichen Doktorwürde
(Dr. sc. nat.)
vorgelegt der
Mathematisch-naturwissenschaftlichen Fakultät
der
Universität Zürich

von

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von
Giebenach BL

Promotionskomitee
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Zürich, 2010

Summary

"What is a valley?" and "where is the valley?". These questions may appear a little clumsy, since they are not often asked to us explicitly; everybody just 'knows' and 'sees' the answers. However, the matter is not so straightforward in geography and its sub-disciplines. Geomorphology – the science of study and characterisation of landforms – and geographic information science deal with formalisations of such terms. Formalisation enables GIS to handle such landform terms in automated, objective workflows while bringing – depending upon the landform term at hand – a degree of human perception into such systems. In the long run incorporation of such naïve geographic knowledge into, and the ability to handle vernacular terms with, GIS could facilitate interaction with users. In the short run characterisations of landforms are of practical interest in, for instance, descriptions of places or the contents of georeferenced images or documents. Compared to traditional, quantitative terrain parameters delineations or characterisations of landforms are less sensitive to errors or uncertainties in the underlying digital elevation model, more easily and readily understandable by human beings and they are essentially qualitative, which makes them more apt to capture the fuzziness of landform phenomena.

Before developing landform characterisation methods this thesis posits an emphasis on in-depth investigation of the semantics of landform terms (something which is not done often) as a requirement. Through a thorough analysis of six geographic standards and additional geomorphology-related reference works and subsequent reconciliation of terms and conceptual hierarchies a tentative taxonomy of landforms is devised. This can be seen as an inventory of landform-related terminology and categories which future approaches at landform characterisation can be built upon.

Regarding delineation and characterisation methods, a bias is found in the literature in that it almost exclusively focuses on topographic eminences such as mountains and hills. Thus in the applied parts, the thesis deals with topographic depressions such as valleys and related features. The derived landform taxonomy allows the development of semantically informed algorithms for the delineation of *valley floors* and the characterisation of *valleyness* in this thesis.

The usefulness of the algorithms for delineating valley floors and for characterisation of valleyness is assessed independently. First, a case study compares the delineated valley floors to naïve geographic knowledge gained from a crowd-sourced online reference work, topographic maps and authorities in the region. The extent of the valley floors in the study

area appears to share common features with the independent data. Further, the classes (peaks, ridges, passes, channels, plains and pits) of what is termed morphometric feature classification interact sensibly with the valley floor delineation. At the same time the morphometric feature classification in itself seems incapable of producing an equivalent delineation.

Subsequently, the valley floor delineation algorithm is employed in a geomorphologic case study to derive low-gradient sediment storage areas in valleys in the European Alps. Comparison with independent empirical data suggests a very good agreement of the automatically derived extent of sediment storage areas ($R^2 = 0.98$, $n = 13$). Making use of a relationship gained from literature, the volumes of the sediment bodies are assessed. Remarkably, the size-frequency relationships of both sediment storage areas and volumes follow power-law distributions over several orders of magnitude with large valleys storing a disproportionately high volume of alpine sediment.

A third case study aims at characterising valleys. To this end three fuzzy valleyness measures are developed which are based to a varying degree on the above valley floor delineation. Since the valleyness measures are developed to mimic the human perception and appreciation of the landform in question, their validity is, consequentially, assessed in a human-subject experiment involving a questionnaire survey. In the survey participants are confronted with georeferenced images and assess the valleyness of the photographer's location. Analyses show that the human assessment of valleyness is related to the algorithmic measures and the correlations yield statistically significant results ($R^2 = 0.35$–0.37, $n = 100$). Accounting for a suspected confounding factor in some of the images and weighing the stimuli according to the associated uncertainty in the human judgment process further increase the goodness of fit of the relations ($R^2 = 0.50$–0.55, $n = 83$).

The contributions of this thesis are diverse. Practically, the thesis offers a tentative landform taxonomy which can inform future research efforts and algorithm development. Further, the thesis suggests methods to delineate valley floors and low-gradient sediment storage areas as well as methods to fuzzily characterise valleys, and investigates their suitability in comparing them to independent data. On a theoretical level, the three case studies demonstrate ways how to better incorporate semantic knowledge into geomorphometric algorithms. Additionally, a research methodology for 'human-centred', semantically rich characterisations of landforms is suggested, which importantly incorporates the assessment of an algorithm's results by contrasting them to the subjective judgment of a large group of human subjects – which, to the author's best knowledge, was done in this thesis for the first time.

Zusammenfassung

“Was ist ein Tal?” und “wo ist das Tal?“. Diese Fragen können einem seltsam erscheinen, da sie kaum je so explizit gestellt werden. Jede und jeder ‘weiss’ beziehungsweise ‘sieht’ die Antworten darauf. Jedoch ist die Sachlage innerhalb der Geographie und ihren Unterdisziplinen nicht so einfach. Geomorphologie – die Disziplin, die sich mit Landformen beschäftigt – und die Geographische Informationswissenschaft arbeiten an der Formalisierung solcher Begriffe bezüglich Landformen. Formalisierung ermöglicht es Geographischen Informationssystemen (GIS), solche Begriffe in automatisierten, objektiven Abläufen einzusetzen. Gleichzeitig kann sie – abhängig davon, welcher Landform-Begriff formalisiert wird – GIS etwas mit der menschlichen Wahrnehmung bereichern. Längerfristig sollte dies dazu führen, dass die Benutzung von GIS einfacher wird. Kurzfristig sind Formalisierungen und Charakterisierungen von Landformen beispielsweise interessant für Beschreibungen von Orten oder von Inhalten von georeferenzierten Bildern oder Dokumenten. Verglichen mit traditionellen, quantitativen Terrainparametern sind Abgrenzungen oder Charakterisierungen von Landformen robuster gegenüber Fehlern oder Unsicherheiten im digitalen Höhenmodell, einfacher und schneller verständlich (auch für Laien) und üblicherweise qualitativ, wodurch sie sich besser zur Erfassung der Unschärfe von Landform-Phänomenen eignen.

Diese Dissertation betont die Notwendigkeit eingehender Analysen der Semantik von Landform-Begriffen *vor* der Entwicklung von Methoden zur Abgrenzung oder Charakterisierung (dies wird nur selten so gehandhabt). Durch eine umfassende Analyse sechs geographischer Standards und zusätzlicher geomorphologischer Referenzliteratur und anschliessender Integration und Abgleichung von Begriffen und konzeptuellen Hierarchien wird eine Taxonomie von Landformen entwickelt. Letztere kann als Inventur der Terminologie im Bereich von Landformen verstanden werden und zukünftige Ansätze der Charakterisierung von Landformen können darauf aufgebaut werden.

In der Literatur findet sich ein Ungleichgewicht im thematischen Fokus von Arbeiten über Abgrenzung und Charakterisierung von Landformen. Die Mehrheit der Veröffentlichungen befasst sich mit topographischen Erhebungen wie Bergen und Hügeln. Daher konzentriert sich diese Dissertation in ihren angewandten Teilen auf topographische Vertiefungen wie Täler und damit verbundene Erscheinungen. Die bereits erwähnte Taxonomie von Landformen hilft in dieser Dissertation dabei, semantisch sinnvolle Algorithmen zur Abgrenzen von *Talböden* und zur Charakterisierung von *Talhaftigkeit* zu entwickeln. Die Nützlichkeit der Algorithmen wird unabhängig voneinander überprüft und bewertet. Eine erste Fallstudie vergleicht automatisch abgegrenzte Talböden mit sogenanntem naiven geographischen Wissen, welches aus einer gemeinschaftlich erstellten und nachgeführten Online-Enzyklopädie, aus topographischen Karten und von Behörden in der betreffenden Region gewonnen worden ist. Die Ausdehnung der Talböden innerhalb des Untersuchungsgebiets weist Übereinstimmungen mit den unabhängig erhobenen Daten auf. Weiter stehen die

Klassen der sogenannten *morphometric feature classification* (Gipfel, Grat, Pass, Rinne, Ebene und Senke) in einer sinnvollen Beziehung zur Talboden-Abgrenzung. Gleichzeitig scheint die *morphometric feature classification* aber nicht geeignet, eigenständig eine gleichwertige Talboden-Abgrenzung vorzunehmen.

Die Talboden-Abgrenzung wird anschliessend in einer zweiten, geomorphologischen Fallstudie verwendet, um flach gelagerte Sedimentspeicherflächen in den europäischen Alpen zu kartieren. Der Vergleich mit unabhängigen, empirisch erhobenen Daten zeigt eine sehr gute Übereinstimmung ($R^2 = 0.98$, $n = 13$). Mithilfe einer empirischen Beziehung aus der Literatur können auch die Volumina der Sedimentspeicher abgeschätzt werden. Bemerkenswerterweise, folgen die Häufigkeitsdichten sowohl der Volumina als auch der Flächen über einige Grössenordnungen hinweg einem Potenzgesetz. Dabei speichern die grossen Alpentäler, flächen- und volumenmässig, einen deutlich überproportionalen Anteil an Sedimenten.

Eine dritte Fallstudie beschäftigt sich mit der Charakterisierung von Tälern. Zu diesem Zweck werden drei unscharfe Masse für *Talhaftigkeit* entwickelt. Diese basieren zu einem unterschiedlichen Grad auf der obengenannten Talboden-Abgrenzung. Da die Masse für *Talhaftigkeit* mit dem Ziel entworfen werden, die menschliche Wahrnehmung und Einschätzung der Landform nachzuahmen, wird deren Güte konsequenterweise in einer Befragung überprüft. In diesem Experiment werden Teilnehmerinnen und Teilnehmer mit georeferenzierten Fotografien konfrontiert und müssen die *Talhaftigkeit* des Aufnahmestandorts einschätzen. Die Analysen zeigen, dass die Einschätzung der *Talhaftigkeit* mit den Resultaten der Algorithmen in statistisch signifikanten Beziehungen stehen ($R^2 = 0.35$–0.37, $n = 100$). Die Berücksichtigung eines mutmasslichen Störfaktors und die Gewichtung der Stimuli gemäss der assoziierten Unsicherheit verstärken diese Beziehungen noch deutlich ($R^2 = 0.50$–0.55, $n = 83$).

Die Beiträge zur Forschung der vorliegenden Dissertation sind vielfältig. Auf der praktischen Seite bietet die Dissertation die Taxonomie von Landformen, die für zukünftige Forschungsprojekte und Algorithmenentwicklung zur Unterstützung beigezogen werden kann. Weiter werden Methoden zur Abgrenzung von Talböden und flach gelagerter Sedimentkörper sowie zur unscharfen Charakterisierung von Tälern eingeführt und deren Gültigkeit im Vergleich mit unabhängigen Daten überprüft. Auf der theoretischen Ebene demonstrieren drei Fallstudien Ansätze, semantisches Wissen besser in geomorphometrischen Algorithmen zu nutzen. Zusätzlich wird eine Untersuchungsmethodik für ‚menschen-nahe', semantisch reichhaltige Charakterisierungen von Landformen vorgestellt. Diese umfasst die Bewertung der Resultate von Algorithmen anhand der subjektiven Einschätzungen von Teilnehmerinnen und Teilnehmern einer Befragung. Eine solche Methodik wird in dieser Dissertation – gemäss dem Wissen des Autors – zum ersten Mal überhaupt verfolgt.

On a personal note…

I would like to bid my heartfelt thanks to:

... the providers of the photographs I used as stimuli in the questionnaire for my human subject experiments. Those were Ronald Schmidt, Ingo Petzold, Martin Tomko and Simone Bircher.

... the beta-testers of the questionnaire. These were Somayeh Dodge, Ramya Venkateswaran and Martin Tomko from the GIS unit as well as Arzu Çöltekin from the GIVA unit within our department. They made sure that my questionnaire was usable on all mixes of platforms and browsers and also contributed feedback on questionnaire items and structure.

... all participants in my questionnaire experiment – there were 810 of them! However, some few of those did not bother to enter answers... I was really surprised how the database records skyrocketed once the e-mails were sent out. A special thank goes to those participants who did not only bother to fill in the questionnaire but afterwards also provided me with important comments. These are contained in Appendix G of this thesis.

... Peter Shary with whom I had an intense exchange about terrain parameters and their computation. He also provided me with his software GISEco.

... Jo Wood and David Mark with whom over the course of my PhD I had several interesting discussions and who both provided me with helpful comments and observations which improved my work and my thesis. I also relied on (and still like to use) Jo Wood's software, LandSerf.

... Stephan Gruber from the 3G unit (Glaciology, Geomorphodynamics & Geochronology) within our department for the time when he with Ross Purves and me organised *Geomorphometry 2009* in Zurich and, basically, for being himself...

... my 'PhD ancestors': Alistair Edwardes, Moritz Neun, Felix Hebeler, Stefan Steiniger, Frank Ostermann, David Caduff, Urs-Jakob Rüetschi;
my 'PhD peers': Patrick Lüscher, Somayeh Dodge, Anna-Katharina Lautenschütz;
and my 'PhD successors': Jan Wilkening, Pia Bereuter, Ramya Venkateswaran, Stefano de Sabbata, Paul Crease, Kenan Bektaş, Marco Salvini and Curdin Derungs; for many interactions.

... Christian Sailer (presently working at ESRI) with whom I could share thoughts about everything (be it *geo*, or not); who shared his view of the geoinformatics business world (a contrast to university life, if you like) and who – when he was employed at the support hotline – served as a helpful point of contact when there were problems with ESRI's ArcGIS (and sooner or later *there are*).

... Ronald Schmidt from the GIS unit, who was always patient and very helpful, whenever I experienced a problem involving said software from said company. Also he would share all his fascinating photography, audio recording and travel photography projects with me and thus not only inspire my ArcGIS workflows but also my leisurely activities.

... Anna-Katharina Lautenschütz from the GIVA unit for conversations about PhD life and other stuff and for going to great lengths to provide me with literature about cognition of space.

... Sara Fabrikant from the GIVA unit for advice on statistical analyses of questionnaires and providing me with literature about human subject testing.

... Elisabeth Cottier, who was the GIS unit's secretary three years into my PhD and who always showed interest in us PhD students, and Annica Scheiwiller, who then replaced Elisabeth. Without them, probably nothing would work (the way it should) within the GIS unit.

... Arzu Çöltekin from the GIVA unit for many interesting and entertaining conversations, for at times paying me favours regarding literature and feedback (e.g. on presentations), for offering well-balanced opinions and motivation when something was difficult and for being a great friend.

... Felix Hebeler, with whom I had the honour to share an office (the "Madlab" as Felix used to call it both in reference to its occupants and to the software Matlab which he often used) during three years. Felix taught my how to "manage my supervisor" (Phillips and Pugh 2000). His wit, his friendliness, keen mind, advice and counsel, or sometimes simply his adjusting of perspectives, his expertise in modelling and in Matlab and his humour lightened and brightened many an office day. Regarding Matlab and fun the 'other Felix' (Felix Morsdorf from RSL) can't be omitted. And Felix Hebeler's formidable bean bag should not go unmentioned here either.

... Robert Weibel who heads the whole thing and keeps it going, with whom over the years (already during my diploma thesis) I always had good talks and who cares for a pleasant and supporting atmosphere within the GIS unit.

... Oliver Korup, who – as I perceived it – spontaneously agreed to be my co-advisor (whether he knew where this would lead to?). I was lucky that Olli worked at the Institute for Snow and Avalanche Research (SLF) in Davos and had well-established contacts with our department. Thus, Olli could often spend time with me during visits in Zurich. I enjoyed and profited a lot from these interactions and also from researching and writing a paper with him.

- ... Ross Purves, who – after advising my diploma thesis – agreed to being my PhD advisor, for (in fact) being more than an advisor (let alone: supervisor), for his mastery of sticks (deadlines, deliverables, weekly meetings) and carrots (shoulder pats, congratulations, support, feedback), for mentoring me and teaching me research, for reading through innumerable paragraphs, chapters and papers and, in doing so, turning 'English' into English, occasionally demanding a reference, at times crossing out words, sentences and paragraphs or shuffling them around wildly and for a constructive, respectful, fun working atmosphere.
- ... all colleagues and friends at the university whom I haven't mentioned so far.
- ... and finally, last but definitely not least, Claudia Bühlmann for always being there for me.

Preface

Naturally, writing this thesis has sometimes felt like being on a travel. Different outcomes, findings, storylines accumulated – a sorted compilation of which is now in your hands. Near the end of writing and sorting and compiling, however, I felt I had to give this thesis an overarching element, which – even though of informal (or for some maybe merely decorative) nature – re-emphasises a remote aim.

Thus, before every major chapter's heading you will find a quotation from the novel *Lenz* by Georg Büchner (1839). Georg Büchner was born 17 October 1813 in Goddelau, Germany. Büchner was a writer, natural scientist and revolutionary. After his upbringing in Germany and his studies in Strasbourg (France) and Giessen (Germany) he worked for the *Hessischer Landbote* which – with its motto *peace to huts, war to palaces!* – agitated the rural populace to revolt against oppression. Soon after, Büchner fled back to France where in the winter of 1835 he finished his PhD thesis about fish titled *Abhandlung über das Nervensystem der Barbe*. That was also the time when he started working on *Lenz*. After the presentation of his thesis and subsequent audition lecture the University of Zurich conferred a doctorate on Büchner. On 18 October 1836 he moved to Zurich and picked up his profession as private lecturer. However, on 2 February 1837 he fell ill with typhus fever and died on 19 February. Büchner is buried in Zurich and the Irchel campus of the University of Zurich (where my department is located) features a Büchner square.

In 1839 *Lenz* saw its initial publication. *Lenz* describes the deteriorating mental state of the writer Jakob Michael Reinhold Lenz. I like the story and included it here to give the reader an idea, what a powerful thing descriptions of landscapes and their phenomena – landforms, weather, vegetation – can be.

I am not naïve – I would never claim that GIScience will ever be able to provide descriptions of landscapes in terms of surface form which could come in any way close to Büchner's phrasings. However, I think daring to try and investigate potential ways how we may advance GIScience in the direction of providing meaningful descriptions of landscapes in terms of surface form is definitely a worthwhile endeavour. In the process of this research endeavour I also made various findings of what some people would call the more down-to-earth, applied kind. I am enthusiastic (to tell you) about both of these perspectives.

Contributors and publications

In different parts of my research I had two contributors, namely Dr. Ross Purves from the Department of Geography of the University of Zurich and Dr. Oliver Korup from the Swiss Federal Research Institutes WSL/SLF (now University of Potsdam, Germany).

These researchers contributed significant parts mainly to the Chapters 4 through 6 (the case studies). Ross Purves was primarily involved in the research about resolution sensitivity covered in sections of Chapter 2 and in research which led to Chapter 4 (and a bit less to Chapter 6), while Oliver Korup mainly contributed to the research presented in Chapter 5. This circumstance is also reflected in the co-authorships these authors have in below set of my co-authored scientific publications (in chronological order):

Straumann RK and Purves RS (2007): Resolution sensitivity of a compound terrain derivative as computed from LiDAR-based elevation data. *Lecture Notes in Geoinformation & Cartography*. Fabrikant SI and Wachowicz M (eds): The European Information Society – Leading the Way with Geo-Information, Proceedings of AGILE 2007, 87–109.

Straumann RK and Purves RS (2008): Delineation of valleys and valley floors. *Lecture Notes in Computer Science*, 5266. Cova TJ, Miller HJ, Beard K, Frank AU and Goodchild MF (eds): Geographic Information Science, Proceedings of GIScience 2008, 320–336.

Straumann RK and Korup O (2009): Quantifying postglacial sediment storage at the mountain-belt scale (not peer-reviewed abstract). *Geophysical Research Abstracts*, 11, 2009 EGU General Assembly.

Straumann RK and Korup O (2009): Quantifying postglacial sediment storage at the mountain-belt scale. *Geology*, 37: 12, 1079–1082.

For transparency contributions are highlighted in footnotes to the respective chapters of this thesis. A complete list of all my publications is contained in the brief curriculum vitae after the appendices (page 287).

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"The 20th, Lenz walked through the mountains. Snow on the peaks and upper slopes, gray rock down into the valleys, swatches of green, boulders, and firs. It was sopping cold, the water trickled down the rocks and leapt across the path. The fir boughs sagged in the damp air. Gray clouds drifted across the sky, but everything so stifling, and then the fog floated up and crept heavy and damp through the bushes, so sluggish, so clumsy. He walked onward, caring little one way or another, to him the path mattered not, now up, now down."

from *Lenz* by Georg Büchner

1 Introduction

In what follows we will first introduce the three rather distinct disciplines and strands of research which form the foundation that this thesis is built upon.

1.1 Geomorphology

Geomorphology is the science and study of "landforms and the processes that create them" (Huggett 2007: 3). As a discipline, geomorphology can be regarded as integral part of either geography or geology or as a science in its own right (Sparks 1986: 1). Within geomorphology itself a distinction can be drawn between a qualitative and a quantitative branch. There has been some controversy about the beginnings of latter quantitative geomorphology (cf. Cockbain 1980, Mark and Warntz 1982). However, some of the early works were clearly those by Cayley (1859) and Maxwell (1870). These were centred on the analysis of contour and slope lines and the regions enclosed by them. Cayley's and Maxwell's work led to the discrimination of certain terrain features (some bearing different names today) like elevations and summits, depressions and immits, knots, ridge and course lines (in the former), bottoms, bars, passes, hills and dales (in the latter).

Ever since those early days describing the landscape around us in terms of the form of its surface has remained an important topic and aim of geomorphology. While Ahnert (1998: 1) puts study of landforms at the heart of geomorphology, Summerfield (1991: 3) emphasises both the form and the processes which create the form as equally important subjects for geomorphology.

Upon closer examination the relationship between form and process is a close and intricate one: The form of the land surface has been described as providing the boundary condition for processes (such as erosion, transport and deposition) acting on it. However, in acting on the surface the processes themselves modify the underlying form – the canvas they are acting on – and thus, finally, the intensity and the patterns of themselves. Thus, land surface form is both the result of past geomorphic processes and the stage for present geomorphic processes (Dehn et al. 2001, Swanson et al. 1988) which re-shape it again for future geomorphic processes.

Pike (1995: 223) has noted that developments in the quantitative understanding of land surface form have lagged behind those in the understanding of process. He saw reasons for this among others in the complexity of terrain and difficulties in measuring it, disagreement on adequate methodology and data collection problems especially in the pre-computer era. Additionally, the multitude of investigations into process is possibly due to the fact that the study of landform is considered "regional", while the study of process is systematic (Sparks 1986: 1) and thus raises hopes to gain insight into the inner workings of the fundamental processes which shape land surface form. Such perspective may tempt researchers and practitioners to regard the study of form as an obsolete endeavour – consider, similarly, the demise of regional geography (cf. Schaefer 1953: 228pp, Grigg 1967: 470p). However, for example, Etzelmüller and Sulebak (2000: 36) recognised the importance of form-centred geomorphometric analyses "either to verify model predictions or to update the topographic surface where model predictions have diverged significantly from reality". They detect "a growing emphasis on the significance of morphology as a control of geomorphological processes" (ibid.) and propose a switch from process study as the key for understanding landforms to morphologic description as key for assessment of process. Beside these wholly geomorphologic motivations, however, a point can be made that land surface forms are of paramount interest to humans for example in place descriptions and the like. This perspective will be picked up in the following section.

1.2 Naïve Geography and Geographic Information Retrieval

Naïve Geography is a relatively recent field of geographic research. The term was coined by Egenhofer and Mark (1995a) in a technical report which was later adapted into a conference article (Egenhofer and Mark 1995b). The authors define Naïve Geography as "the body of knowledge that people have about the surrounding geographic world" (ibid: 4). This definition is closely related to Hardt's (1992, cited in Egenhofer and Mark 1995b: 3) earlier definition of Naïve Physics (Hayes 1979), a discipline which in part already picked up Naïve Geography issues. At first glance Naïve Physics and Naïve Geography seem quite similar, however, as the name suggests Naïve Geography is more specific on the domain of geography, while Naïve Physics not exclusively, but often, deals with manipulable (table-top rather than geographic space; Montello 1993) objects.

Naïve Geography is characterised as a body of theories of paramount importance to a new generation of geographic information systems (GIS) "that can be used without major training by new user communities such as average citizens, to solve day-to-day tasks" (Egenhofer and Mark 1995b: 1). So, besides the opportunity to get to understand how people represent and interact with their spatio-temporal environment, the user base of GIS could benefit from and probably be broadened through the incorporation of naïve geographic knowledge and reasoning into GIS; for, "(...) we see a big gap between what a human user wants to do with a GIS, and the spatial concepts offered by the GIS. Today's GIS do not sufficiently support common-sense reasoning; however, in order to make them useful for a wider range of people (...) it will be necessary to incorporate people's concepts about space and time and to mimic human thinking; (...)." (Egenhofer and Mark 1995b: 5). Today, a user cannot query a GIS for all instances of landform categories such as mountains or valleys, nor sensibly for specific instances since it is in some sense unknown where for instance the Matterhorn in Switzerland (Derungs and Purves 2007) or Helvellyn in the UK (Fisher et al. 2004) lie.

There are two principal research strands in geographic information science related to Naïve Geography: one concerning the conceptualisation, definition, determination, representation and analysis of vague objects and another concerning the derivation and use of qualitative relationships between such objects (or for the sake of simplicity between determinate objects); or, concisely, after Montello et al. (2003: 186): *regions* and *spatial relations*. According to Worboys (2001: 635) a spatial relation is also vague, when it complies with two requirements: namely the existence of borderline cases and susceptibility to Sorites paradox (being Sorites-susceptible; cf. Fisher 2000a, Goldstein 2000).

More recently than Naïve Geography, the topic of Geographic Information Retrieval (GIR) has become a topic among researchers dealing with vast amounts of relatively unstructured, spatially referenced data such as digital libraries or data on the World Wide Web

(Larson, 1996, Jones and Purves 2008), the SPIRIT project (Spatially Aware Information Retrieval on the InterneT; Jones et al. 2002, Purves et al. 2007) being an example of an initiative in the latter context.

GIR has been defined as "the provision of facilities to retrieve and relevance rank documents or other resources from an unstructured or partially structured collection on the basis of queries specifying both theme and geographic scope" (Purves and Jones 2006). An important task in dealing with a GIR query is the "geometric interpretation of the meaning of vague place names (...) and of vague spatial language such as 'near'" (Jones and Purves 2008: 220). Consequentially, GIR has helped to foster research into the afore-mentioned concepts pertinent to Naïve Geography (Purves et al. 2007): vague regions and vague spatial relations (e.g. Edwards 1993, Altman 1994, Robinson 2000, Worboys 2001, Montello et al. 2003, Cai et al. 2003).

1.3 Digital terrain modelling

Weibel and Heller (1991: 269p.) define digital terrain modelling as encompassing the tasks of digital terrain model (DTM) generation, manipulation, interpretation, visualisation and application. It needs to be noted, that Weibel and Heller (ibid.) intentionally use the term *digital terrain model* (DTM) over *digital elevation model* (DEM) in their context despite the wider meaning of the former (cf. Li et al. 2005: 8). Regarding the modelling itself, authors sometimes also refer to *digital terrain analysis* (e.g. Wilson and Gallant 2000, Zhou et al. 2008). However, in adopting the definition by Weibel and Heller, analysis is subsumed largely in the task of interpretation.

Currently, there is a wide range of spatial resolutions at which DEMs are available and at which digital terrain modelling is carried out. Medium resolution (i.e. 20–50 metres) DEMs are typically the domain of national mapping agencies. When one desires to address questions on a larger spatial extent, these data exhibit problems such as differences in resolution, in the data capturing and processing methodology and possibly different spatial (horizontal and vertical) reference systems across countries.

Recent years, however, have seen the advent and establishment of new methods of terrain data capture. The two most important developments with the potential to reduce some of the shortcomings of terrain data coverage and accuracy (Pike 2002) occurred at opposed ends of the scale spectrum.

At very fine resolutions the development and refinement of (airborne) laser scanning (ALS) technology offers new possibilities (Li et al. 2005: 50, Fowler 2001). While already in the 1960s researchers experimented with lasers in remote sensing, LiDAR (Light detection and ranging) first saw experimental deployment only in the 1980s (Flood 2001a). In subsequent decades the technology has been adopted more and more by the commercial sector (Flood 2001b).

At a comparatively coarse resolution the Shuttle Radar Topography Mission (SRTM) was a major breakthrough with respect to its near-global coverage of terrain data generation. This is currently followed up at a – at least *nominally* (Straumann and Purves 2007) – finer resolution by the ASTER G-DEM project (ERSDAC 2007).

The Shuttle Radar Topography Mission (SRTM) was launched in 2000 aboard the Space Shuttle. SRTM's two radar antennas captured terrain information covering nearly 80% of the earth's land surface. The enabling technology for SRTM, interferometric synthetic aperture radar (InSAR) had emerged in the late 1980s and 1990s (Zebker and Goldstein 1986). SRTM data is available in two resolutions: SRTM-1 at 1 arc second resolution (roughly 30 metres depending on latitude; publicly available for the USA) and SRTM-3 at 3 arc seconds resolution (roughly 90 metres depending on latitude; available for the rest of the world) (Farr et al. 2007). The latter data was used within this thesis.

The continuing improvement of availability of both data on one hand and hardware and software for handling and analysis on the other hand fosters research in, and application of, digital terrain modelling. Especially data innovation, as described above, helped spark new fields of research and application. It is probably not by accident that along with the broadening of available DEM resolution range at relatively (and increasingly) low cost there can be seen a growing recognition and acknowledgement of the importance of scale in geomorphometry (cf. Purves and Korup 2007; for the importance of scale in geomorphology cf. Wood 1996, Tate and Wood 2001). This recognition of the potential criticality of scale has led some researchers to turn to the investigation of scaling issues within geomorphometry, digital terrain modelling and related fields (e.g. Vieux 1993, Wolock and Price 1994, Zhang and Montgomery 1994, Gao 1997, Brasington and Richards 1998, Walsh et al. 1998, Florinsky and Kuryakova 2000, Sørensen and Seibert 2007). More specifically, regarding geomorphometry and this thesis, there is a growing body of research regarding the multi-scale nature of landforms and landform elements (e.g. Wood 1996, Fisher et al. 2004, Schmidt and Andrew 2005, Deng and Wilson 2007).

1.4 Aims of the thesis

The aim of this thesis is twofold:

Firstly, the thesis sets out to investigate the ontology of landforms. There is a vast amount of literature describing landforms, their characteristics and interrelationships. A first part of this thesis is devoted to structuring the *universe of discourse* of geomorphology with regard to landforms. Such a universe of discourse is defined as “an inclusive class of entities that is tacitly implied or explicitly delineated as the subject of a statement, discourse, or theory” by the Merriam-Webster Dictionary (2010). The intended contribution is the provision of a structured universe of discourse for the task of landform extraction or characterisation in form of a taxonomy of landforms.

Secondly, the thesis investigates ways to build extraction or characterisation algorithms for a small subset out of the breadth of landforms. These algorithms shall be informed by knowledge gained in the first part of the thesis. Subsequently, the plausibility of obtained results shall be tested. This practical part will employ coarse resolution SRTM data; as a consequence, the ontological investigations in the first part of this thesis will focus on landforms which are large enough to be detectable in said data.

After reviewing the state of the art, research questions covering these research aims will be formulated in Section 2.5.

1.5 Structure of the thesis

The remainder of this thesis is organised as follows:

Chapter 2 presents the scientific background of this thesis by introducing the ontological study of landforms, research regarding terrain parameters and their sensitivity to DEM resolution and developments in the field of landform (element) modelling. The chapter further entwines the three disciplines introduced in the above sections. It is completed by identifying research gaps and compiling related research questions.

Chapter 3 forms the first half of the ‘main part’ of the thesis. Therein the extraction of domain knowledge about landforms from several standards is summarised and discussed and a tentative taxonomy of landforms is presented.

The second half of the 'main part' of the thesis comprises three chapters dealing with case studies applying digital terrain modelling methods to a defined set of categories partly gained from the investigations in Chapter 3.

Chapter 4 presents the first case study dealing with the extraction of valley floors from a DEM and comparing the derived features with the extent of valleys estimated from what we term Naïve Geography sources.

Chapter 5 details the second case study which is centred on geomorphological interpretation and further analysis of the valley floors which are related to sediment deposits in that context.

Chapter 6 presents the third case study investigating an extension of valley floor delineation which yields a fuzzy measure of valleyness. The usability and representativeness of the measure is assessed in an experiment encompassing human subject testing.

All three case studies follow a parallel pattern in so far as each presents relevant scientific background and methodology. Also each case study presents and discusses results and draws conclusions.

Chapter 7 subsequently summarises and discusses the overall findings of the thesis, especially in the context of the research gaps identified and the research questions phrased in Chapter 2. In the process, Chapter 7 also highlights contributions, insights and potential future research directions and developments.

"Only sometimes when the storms tossed the clouds into the valleys and they floated upwards through the woods and voices awakened on the rocks, like far-echoing thunder at first and then approaching in strong gusts, sounding as if they wanted to chant the praises of the earth in their wild rejoicing, and the clouds galloped by like wild whinnying horses and the sunshine shot through them and emerged and drew its glinting sword on the snowfields so that a bright blinding light knifed over the peaks into the valleys; or sometimes when the storms drove the clouds downward and tore a light-blue lake into them and the sound of the wind died away and then like the murmur of a lullaby or pealing bells rose up again from the depths of ravines and tips of fir trees and a faint reddishness climbed into the deep blue and small clouds drifted by on silver wings and all the mountain peaks, sharp and firm, glinted and gleamed far across the countryside, he would feel something tearing at his chest, he would stand there, gasping, body bent forward, eyes and mouth open wide, he was convinced he should draw the storm into himself, contain everything within himself, he stretched out and lay over the earth, he burrowed into the universe, it was a pleasure that gave him pain;"

from *Lenz* by Georg Büchner

2 Background

Geomorphometry is defined as the quantitative measurement and analysis of the form of the earth's surface. It is thus closely tied to both the field of geomorphology (Section 1.1) and that of digital terrain modelling (Section 1.3). The current section will review research in the overlapping fields of geomorphology and digital terrain modelling.

Firstly, ontological knowledge about conceptualisation of geographic categories and, more specifically, of landforms will be reviewed.

Secondly, simple means of terrain characterisation such as the computation of terrain parameters from digital elevation models (DEMs) will be introduced and relevant research reviewed. This will mainly focus on different implementations and resolution sensitivity; these are both factors which have to be considered in any digital terrain modelling endeavour and thus also apply when stepping from terrain parameter computation to landform (element) modelling.

Thirdly, research concerning landform element and landform classification and modelling shall be summarised, before research gaps are identified and research questions phrased.

2.1 Ontology of geographic categories

2.1.1 Definitions: Ontology

The term *ontology* has meanings both in the realm of philosophy (traditionally) and in the field of computer science (more recently) (cf. Schuurmann 2006). In the latter it is used in such diverse areas as knowledge engineering, representation and management, qualitative modelling, database design, information retrieval and agent-based system design (Guarino 1998).

As an uncountable noun, *ontology* is defined by the Oxford English Dictionary (OED 2009) as “the science or study of being; that branch of metaphysics concerned with the nature or essence of being or existence.” Used as a countable noun the meaning according to OED is more specific, namely, “a theory or conception relating to the nature of being”. However, “different senses are assumed by the philosophical community and the Artificial Intelligence community (and, in general, the whole computer science community) for the latter term” (Guarino 1998: 4). Guarino (ibid.) regards a philosophical ontology (here, countable) “as a particular system of categories accounting for a certain vision of the world”. This system does not depend on any special language. In computer science, however, an ontology is an “engineering artifact, constituted by a specific vocabulary used to describe a certain reality, plus a set of explicit assumptions regarding the intended meaning of the vocabulary words”. The most concise (and often cited) definition of such ontologies was given by Gruber (1993: 199): “An ontology is an explicit specification of a conceptualization”, where the last term means “objects, concepts, and other entities that are presumed to exist in some area of interest and the relationships that hold among them”.

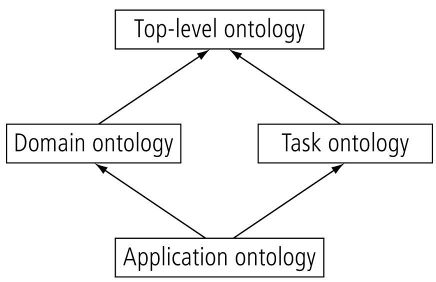


Fig. 1: Kinds of ontologies (arrows represent specialisation relationships) (after Guarino 1998: 7).

Formally, ontologies can have different levels of specificity. In the simplest case an ontology consists of a hierarchy of concepts (a taxonomy) described in natural language. In more complex settings an ontology can be specified in a semi-formal language such as Unified Modeling Language (UML) or, more complex, in Description Logic which can be interpreted by computers (Bittner and Winter 2004).

Further, ontologies can have different scope and focus (Fig. 1). Top-level ontologies are the most general ontologies describing very fundamental concepts such as space, time, object or process. Domain and task ontologies are more specific and aimed at defining the vocabulary of a particular domain (e.g. soils) or pertaining to a specific task (classifying and delineating pedons). Lastly, application ontologies describe concepts pertaining both to a particular domain and task (Guarino 1998).

In this research the term ontology will mostly be used in the sense of Guarino's (1998: 4) philosophical ontology, namely "a theory or conception relating to the nature of being" (OED 2009) − at least where we are employing the term and not quoting other authors. For the product of the ontological research in this thesis which pertains to a computer science ontology *sensu* Guarino the more comprehensible term *taxonomy* will be used. This both avoids potential confusion within this thesis (at least as far as it does not concern quotations) and specifies the level of formality aimed for within our ontological research.

An ontological artefact even when informal is considered sufficient for improving communication between humans, for example for agreeing on standards (Bittner and Winter 2004). In terms of scope the ontology / taxonomy which will be dealt with in this section and in Chapter 3 can be regarded as pertaining to a domain ontology. While different domain ontologies can encompass the same objects, how objects are conceptualised depends on the domain at hand, for instance "an architecture or mining ontology would look at space in a very different way from how a topographic ontology needs to consider space" (Kovacs et al. 2007). The ontology which this research will investigate is that of geography and latterly – more specifically – of geomorphology.

2.1.2 The cause for geographic ontology research

Need for ontological studies. Ontologies of geographic categories (kinds or entity types) help in understanding the geographic world and *universe of discourse*. Besides these, Smith and Mark (1998) highlight at least the following practical benefits:

– understanding how different groups of humans manage or fail to exchange geographic information
– understanding distortions of our cognitive relations to geographic phenomena
– providing GIS with characteristics which enable them to deal with geographic entities
– capturing the semantics of entity types in data exchange standards

Dealing with geomorphology, Dehn et al. (2001) advocate the introduction of more semantic information into the process of landform characterisation because of, for instance, interoperability problems such as heterogeneity of vocabulary and, worse, cognitive semantic heterogeneity. Straumann and Purves (2008) and Straumann (2009) highlighted the importance of semantics for the unification of vocabulary, the informativeness of landform characterisations and the improvement of algorithms dealing with landforms or landform elements (see Section 2.3.1 on these latter terms).

Ontology for geography and geomorphology. Is there a need for geography and, more specifically, geomorphology to conduct ontological studies of their own?

To answer this question, consider the following: Spatial cognition research has seen some effort to classify different kinds of spaces. For example Montello (1993) postulated multiple spatial psychologies of space, arguing that space is not scale-independent. He posited that space can be subdivided into *figural space* (space projectively smaller than the human body; no movement is required to apprehend spatial properties of objects), *vista space* (space projectively as large or larger than a human body; can be apprehended from a single viewpoint), *environmental space* (projectively larger than a human body; not directly apprehensible without locomotion) and *geographical space* (projectively much larger than a human body; not directly apprehensible through locomotion but rather through artefacts in figural space (e.g. maps)). Similar classifications have been put forward by Ittelson (1973) or Gärling and Golledge (1989); a concise graphic overview of numerous such approaches is given by Freundschuh and Egenhofer (1997). Egenhofer and Mark (1995b: 3) argue that there is “strong evidence (...) that people conceptualize geographic spaces differently from manipulable, table-top spaces”. These potential discrepancies led them to coin the term *Naïve Geography*, since they did not see geographic concepts adequately subsumed in Naïve Physics (see Section 1.2).

Mark et al. (1999) established the link from such models of geographic space to the ontology of geographical entities; together with Mark (1993) they posited this ontology be studied. While there are the well-established works by Rosch (1978, as cited in Mark 1993) and Lakoff (1987) on categorisation, these largely relied on the study of manipulable objects rather than geographic objects. However, Smith and Mark (1998) pointed out that for table-top and similar objects the *what* and the *where* are almost always independent, whereas in the geographic world they are “intimately intertwined”. Besides, categorisation in geographic space is often scale-dependent (e.g. *pond* versus *lake* versus *sea* versus *ocean*), more likely to be individually or culturally variable, and dependent on boundaries as salient elements. Also, categorisation of a thing and its boundary interact, for example, “if a given topographic feature is identified as a marsh, then its boundary may be located farther up the slope than would be the boundary of the same feature if it had been identified as a lake” (ibid.).

Because of such special aspects which apply in geographical space, the investigation of geographic categories is clearly warranted. It should also extend to and include the ‘geographer’s tools’ such as remote sensing images, vector data and digital elevation models (Câmara et al. 2001). The point is not, however, that geographic ontology research should stand apart from ontology research in other disciplines – on the contrary, it is hoped that an eventual geographic ontology (in the sense of an engineering artefact) will be connected to some upper-level ontology (e.g. SUMO (2009), DOLCE (LAO 2009), BFO (2009)) which will define such basic ‘building block’ concepts like *space*, *matter* or *process* (e.g. along the model of Nichols (2004)).

The next sections will summarise some of the key findings of (geographical) ontology research.

2.1.3 Categorisation

Categorisation occurs “whenever two or more distinguishable objects or events are treated equivalently. This equivalent treatment may take any number of forms, such as labelling distinct objects or events with the same name, or performing the same action on different objects” (Mervis and Rosch 1981: 89). Being confronted with different stimuli, organisms may treat them equally based on categorisation which can thus be considered one of the most basic functions of living creatures (ibid., Lakoff 1987, Sigala et al. 2002). Categorisation seems to be close to the core of human cognition. “Without the ability to assign unfamiliar ‘things’ to categories, every new scene or view or other sensory input would have to be figured out from some sort of first principles. But with a set of categories, and default attributes for category members, we can learn a lot about a thing just by assigning it to some category” (Mark 1993: 270p).

Perception may be an important motor for the recognition of boundaries and thus objects. Smith and Varzi (2000: 405) illustrated the propensity of humans to delineate objects with sharp boundaries even where there are no such boundaries referring to paintings by the pointillist Seurat (Fig. 2). According to cognitive science, humans indeed tend to discretise even when confronted with essentially continuous phenomena (Smith and Mark 1998); consider for example soil maps in geography or GIS. This human ability to carve boundaries into continua is not only crucial for object delineation but can also be observed in action in the formation of categories, since these can be regarded as objects in, usually continuous, parameter space. Being a means of abstraction, categorisation of objects helps lessen the cognitive load implied in dealing with the world. The advantages and disadvantages of this feature are nicely put by Mark (1993: 271): "Of course, there is a risk of misinterpretation, but the alternative would be chaos."

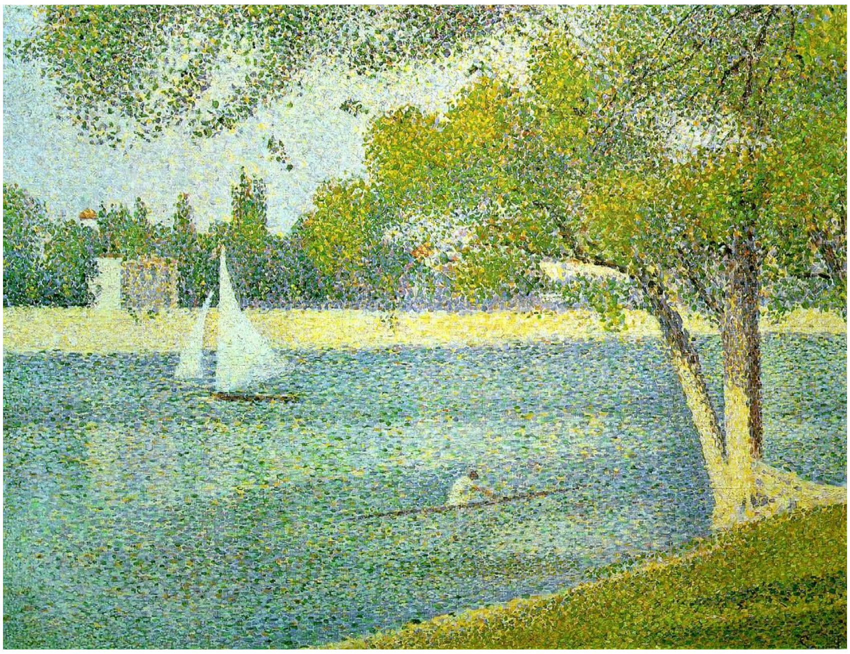


Fig. 2: Painting *La Seine à la Grande-Jatte* by Georges-Pierre Seurat (1888) (Art in the Picture 2009).

Exactly what kinds of boundaries are found or imposed in the geographic domain is the subject of the following two sections.

2.1.4 Fiat and bona fide boundaries and objects

The boundaries of geographic objects are equally important as the constituents within the interior of such objects (Smith and Mark 1998). Most authors distinguish two kinds of boundaries: *bona fide* (Latin for "in good faith") and *fiat* (Latin for "let there be"). The first is manifest in reality as a marked boundary or discontinuity of some sort. Geographic examples are coastlines, drainage divides, rivers or their shores. Conversely, fiat boundaries are imposed onto reality by human acts of decision such as laws, political decrees, phenomena of human cognition related to these, collective custom or informal consensus manifest in linguistic usage (Smith 1995, Smith and Mark 1998, Thomasson 2001: 151).

A typical example of devising fiat boundaries (and thus fiat objects) is the "drawing of lines on a map"; for instance, by Thomas Jefferson regarding the states of the Northwest Ordinance (Smith 1995, 2001) or by Pope Alexander VI regarding the Spanish and Portuguese spheres of influence (Encyclopædia Britannica 2009). While it is important to point out that the *fiat – bona fide* dichotomy is not entirely without problems and not agreed upon by all theorists (Smith 1995), it is a useful tool to characterise also geographic objects.

While objects which are demarcated solely by bona fide boundaries are termed *bona fide objects*, those with fiat boundaries or a mixture of bona fide and fiat boundaries are termed *fiat objects* (Smith and Varzi 2000: 403). Smith and Mark (1998) made a yet finer distinction. On their "mesoscopic stratum of spatial reality" they divided objects into those of "straightforwardly physical sort", into "geographic objects", which are part of the physical world but exist only due demarcations through human cognition, and into "geopolitical objects" such as nations, which are more than physical. For now we will stick with objects which exist by virtue of fiat boundaries (i.e. geographic and geopolitical *sensu* Smith and Mark (1998)), later the discussion will focus onto geographic objects alone.

Typical fiat objects are administrative divisions such as countries, cities or parcels – especially where the boundaries lie askew any geographic discontinuities (as is often the case for e.g. states of the USA). Clearly, fiat boundaries of such objects can over time acquire boundary-markers which render them more manifest and tangible (Smith 1995). Boundaries of landforms such as mountains or valleys "are also at least partly of the fiat type, although here the boundaries may result from cognitive rather than from legal or political processes" (Smith and Mark 1998). This does not mean, however, that the landforms themselves are mind-dependent; only some of their boundaries. The physical existence of, for example, a mountain is mind-independent (it does have an "independent foundation in the pieces of land that have such properties as being bounded in a certain way" which makes it different from "mere mental constructs or figments of the imagination"), although the existence of some of its boundaries may depend on human cognition (Thomasson 2001: 150; Smith 2001: 142p, Smith 1995; similarly, Smith and Mark (2003) answered the question "Do mountains exist?").

2.1.5 Crisp and fuzzy boundaries and objects

Besides the distinction of fiat and bona fide boundaries and objects there is the differentiation into *crisp* (or hard) and *fuzzy* (or indeterminate, graded) boundaries and objects. In fact, there are relatively few spatial objects which have well-defined, hard boundaries. Such objects are usually of administrative nature like land parcels, nature reserves, states, or man-made objects like highways, streets and houses (Erwig and Schneider 1997). Indeed, "many [geographical] objects – deserts, valleys, mountains, noses, tails – are delineated not by crisp outer boundaries but rather (on some sides at least) by boundary-like regions which are to some degree indeterminate" (Smith 2001: 143, Smith 1995). Erwig and Schneider (1997: 301) named "mountains, valleys, biotopes, oceans, and many other geographic features which cannot be rigorously bounded by a sharp line" as examples of fuzzy spatial objects.

Dehn et al. (2001: 1008) attributed this fuzziness which is typical for landforms to "semantic heterogeneity" which in turn is caused by the fact that a continuous surface is "artificially delimited into units. As a result, perceptions of landform features are often indistinct and features are not defined disjointly." This is illustrated by the terms *mountain*, *hillslope* and *valley* for which Dehn et al. (2001) argued that while they are clearly ordered into a toposequence, their transitions are unclear. As a consequence of their fuzziness, one can even think of geographical objects as being partly overlapping (e.g. a hill and a valley), something which is not sensible for non-geographical objects like dogs and apples (Mark et al. 1999: 286). Even worse, besides fuzziness (spatial vagueness) there is semantic vagueness, which will be discussed in the next section.

Importantly, despite all these intricacies, even for generally fuzzy objects some boundaries are very determinate: "we can all agree (...) that it is obvious for example where the top of a mountain or the end of a cape is to be found. The crisply determined features of such entities – for example the heights of mountains – can be looked up in reference books." However, there is a twist: "But where is the boundary of Cape Flattery on the inland side? Where is the boundary of Mont Blanc on the French and Italian sides?" (Smith 2001: 144). These questions are not easy at all to answer. Sadly, such undefined boundaries are not only of academic interest, since – as Couclelis (1996: 55, cited in Smith and Varzi 1997: 105) pointed out – violent conflicts develop over such issues.

2.1.6 Prototypicality and semantic vagueness

Classical theory of categorisation (McCauley 1987) which posits that categories are based on shared properties is not entirely wrong, however, it is only part of the story (Lakoff 1987: 5). Still, classical theory has been influential in science and led to the latter handling categories as mathematical sets, of which something could be either a member or not. Every member of such a set would be an equally good representative of the respective category. However, Rosch (e.g. 1978) investigated the implication of classical theory that if categories are defined by properties shared by all members, then no member should be more representative of the category than others. She found that her own studies and those by other researchers showed that generally best examples (prototypes) of categories exist, however. (Lakoff 1987: 7; Mark et al. 1999: 284). "For most categories and for most people, some members are better examples of the class than are others; furthermore, there is a great degree of agreement among human subjects as to what constitutes a good example. And sometimes, it is difficult to know whether or not some observed case is a member of a given class." (Mark 1993: 271).

Fig. 3: A prototypical example of the *mountain* category. This is part of a set of 260 pictures which were standardised on name agreement, image agreement, familiarity and visual complexity (all fundamental to memory and cognitive processing) (Snodgrass and Vanderwart 1980).

An example of prototypicality which is sometimes given are different species of birds. Most people would agree that a sparrow is a fine example of the *bird* category, whereas, for instance, ostrich, emu, kiwi, penguin, rhea or the extinct dodo and elephant bird (all of which are flightless) are less good representatives – they are considered to reside on the 'fringe' or in the 'penumbra' of the *bird* category. Based on such findings, Rosch and Lakoff suggested that categories can have a radial structure with the prototypical meaning in the centre surrounded by a penumbra of less typical instances (Mark 1993, Smith and Mark 1998). The same applies to landforms. One can easily think of prototypical instances of, for example, the *mountain* or the *valley* category (Fig. 3). Possibly, prototypicality is even stronger in this field, because its dual – the semantic vagueness inherent in landform categories – is more pronounced than for example in the realm of biological taxa. Smith and Mark (1998) found an aspect of this semantic vagueness to be "an element of arbitrariness or fiat (...) in the domain of our concepts themselves". Indeed, many landform categories are not easily separated from each other (think: *mountain* versus *hill* or *ravine* versus *valley*) and some cases instances are conceivable where one could be tempted to accommodate a landform into two categories at the same time.

The situation of semantic vagueness is exacerbated by the notion of the land surface being a *palimpsest* (literally, a piece of parchment which has been repeatedly written on and scraped clean again; Chorley et al. 1984: 3). The notion *palimpsest* implies that the land surface is exposed to different regimes and a mixture of processes. Thus, it can develop a form which may bear resemblance to several landform categories (also, different landforms at different spatial scales can overlap, but this discussion is postponed to Section 2.3.4) or a landform of a certain category can turn – via intragrades – into a likely member of another category – making matters much more complicated for anyone interested in classifying it.

2.1.7 Modes of creation of fiat objects and intercultural variance

Summarising some of the above, as Câmara et al. (2001) posited for a remote sensing image, we could assert that a digital elevation model is best thought of as a field at the measurement level but contains fiat objects with usually fuzzy boundaries at the classification level. "A spatial analysis fiat object owes its existence to (1) the notion of a corresponding object in the world, (2) an act of measurement (in this case, the remote sensing process), and (3) a creative human act of spatial analysis." (ibid: 477). However, we would like to model the results of our 'act of spatial analysis' (not necessarily the act itself) after those of the act of human "fiat parsing of the elevation field" (Smith and Mark 2003: 420), i.e. we would like to be able to characterise landforms from a DEM as humans would from their surroundings.

Thus we need to know how fiat objects such as landforms are created in the first place. Thomasson (2001: 152pp) divided that process into two alternatives: *creation by token* and *creation by type*. "Creation by token" refers to a situation where humans establish ad hoc facts about an instance of a category by collective custom which, for example, states which pieces of land do count as part of a mountain and which do not. This is "a slow and painstaking operation (...). Much efficiency is gained when we move to the creation of facts by type rather than by token." (ibid.). Creations by type can take place given that there are "general principles that stipulate sufficient conditions for the creation of objects of that type" (ibid.). We argue that for instances of landform categories we can say that they are usually created by type; and that the boundaries of every individual landform are not agreed upon by token.

Size, shape and context are important criteria for the definition of landform categories. This is contrary to the realm of living things, where size is merely an attribute which is subject to change with time. Since the latter is less so in the case of landforms, size and shape can be used at all for categorical distinctions (Smith and Mark 1998). In fact in some instances size together with context is *the* criterion. Dehn et al. (2001: 1008) argued that, for instance, the Andes' altiplano would usually not be categorised as a slope but as a plain because of its large size (which renders some inclination and surface undulation less important) and because of the neighbouring mountain chain with its contrasting, much steeper slopes. Regarding context Dehn et al. (ibid.) also made the obvious point that both a valley and a mountain cannot exist without their accompanying hillslopes.

So, notwithstanding their fuzziness, landform categories do have a semantic core, mostly defined by size, shape and context, which may be agreed upon amongst individuals (possibly of certain cultural groups).

Some considerations are in order regarding those parentheses: Since bona fide objects are not dependent upon fiat boundary-making they are – compared to fiat objects – less prone to vary inter-personally and inter-culturally. Fiat objects such as certain landforms, however, are imposed onto the world by human cognition and thus more subject to such variance (Smith and Mark 1998, Mark and Turk 2003: 32). Additionally, cognitive representations of a category may be modified through social and cultural interactions, education, imposed definitions or agreed instances of said category (Smith and Mark 1998). Even the degree to which individuals divide a continuous landscape into landforms or, generally, objects may be culture-dependent (Mark and Turk 2003: 33). For the Yindjibarndi people Mark and Turk (2003) showed that they use a fundamentally different conceptualisation of convex landforms and water bodies than the English language. This led to the formation of the field of *ethnophysiography* which investigates such culture-specific notions of landscape elements.

However, while acknowledging the findings of this latter strand of research, we assume that the conceptual subdivision of landscapes into landforms is relatively homogeneous in what is sometimes termed the 'Western culture'. Clearly, there will be differences through different languages and different etymologies of those languages as well as through exposure to different landscape types and other factors such as potentially different affordances tied to some surface form. However, we assume we can still speak of a common conceptual core onto which a majority of the people living in the 'Western world' can agree.

2.2 Terrain parameters

In terms of surface characterisation we now take a step down to the more basic level of mathematically definable terrain parameters. Geomorphometry, and digital terrain modelling in general, knows a range of terrain parameters (Moore et al. 1991, Li et al. 2005, Hengl et al. 2003, Olaya 2009). Depending upon author or context terrain parameters are also termed "geomorphometric parameters" (Mark 1975), "topographic variables" (Shary 1995, Gao 1997), "geomorphometric variables" (Gao 1997), "topographic attributes" (Gallant and Wilson 1996, Wilson and Gallant 2000), "morphometric variables" (Shary et al. 2002), "terrain derivatives" (Kienzle 2004) or "land-surface parameters" (Hengl and Reuter 2009). The exact terminology in this respect does not matter too much. However, it should be noted that from the above one may well use compounds with "morphometric" instead of "geomorphometric", since many parameters (especially the ones which do not require a gravitational field) can be computed for other surfaces than the land surface and are investigated in other fields than geographic information science (cf. Pike 2000a,b and 2001a,b on the similarities and differences of digital terrain modelling and industrial surface metrology). Also, the term "terrain derivative" should be used with care, since, for example, Kienzle (2004) uses the term not exclusively for mathematical derivatives of the surface, but for parameters that can be 'derived' from terrain data in the broader sense of the word (as did Straumann and Purves (2007)).

There are different classifications to order terrain parameters. Both Li et al. (2005) and Hengl et al. (2003) group terrain parameters according to the purpose of the analysis (e.g. geometric, morphological, hydrological and visibility). However, the simpler, not application-based classification by Wilson and Gallant (2000) seems more attractive. They distinguish primary terrain parameters which are "computed directly from the DEM" and secondary terrain parameters that "involve combinations of two or more primary attributes" (Gallant and Wilson 1996: 713). Table 1 in Appendix A gives an overview of some prominent primary terrain parameters in this sense. The remainder of Appendix A lists some secondary terrain parameters. An example of a secondary parameter is the topographic (wetness) index (TWI) or compound topographic index (CTI) (Beven and Kirkby 1979, Quinn et al. 1995):

$$\mathrm{TWI} = \ln\left(\frac{A_s}{\tan(\beta)}\right) \tag{1}$$

where: A_s: Specific catchment area; β: slope gradient

Thompson et al. (2001) noted that the accuracy of DEMs and terrain parameters derived from DEMs depend on factors like the source of the data, the methods for turning source data into a DEM, the DEM data model and structure (raster, contours, TIN), the horizontal and vertical resolution, algorithms used to compute terrain parameters and the topographic complexity of the landscape. In what follows we review and discuss research relating to some of these factors. The emphasis is on algorithms for deriving terrain parameters and the influence of the horizontal resolution of DEMs on resulting terrain parameters. Since terrain parameters are input to landform (element) modelling, consideration of such factors is important in landform-related research. Questions regarding vertical precision, sources of DEMs and methods for creating DEMs will necessarily also be briefly touched upon in both sections.

2.2.1 Implementation of mathematical surface derivatives

Partial surface derivatives (note, here 'derivatives' in the mathematical sense) form the basis of the computation of many terrain parameters. For example, from them slope gradient, slope aspect and also different curvatures can be computed (Shary et al. 2002: 28). There are several algorithms to estimate various partial derivatives of surfaces. One of the most prominent ones is termed the *Evans-Young method* which is detailed in Appendix B. Numerous algorithms have been put forward for the calculation of first- and second-order derivatives approximating partial derivatives usually through finite differences (LeVeque 2005) of different orders. In fact there are so many algorithms that there is considerable confusion about which is which – also, some algorithms yield identical results. Table 1 features a selection of methods and elucidates (perceived) authorship, similarities and identities – where feasible. The terms f_x, f_y and f_{xy} used in Table 1 refer to partial derivatives of fitted surfaces, where:

$$f_x = \frac{\partial z}{\partial x} \tag{2}$$

$$f_y = \frac{\partial z}{\partial y} \tag{3}$$

$$f_{xy} = \frac{\partial^2 z}{\partial x \partial y} \tag{4}$$

The subsequent section will use the method name given in the first column in Table 1 for referring to a specific algorithm.

Table 1: Algorithms for computing approximations to partial derivatives of surfaces. For more details on the methods refer to the original publications or see the comments in Skidmore (2007) discussing names and attribution of the methods.

Method name	**Attributed to**	**Related to**	**Description**
Sharpnack-Akin	Sharpnack-Akin (1969)	Horn; Slope gradient and aspect identical to those of a least-squares linear surface fitted to eight neighbouring cells and to those of an unconstrained least-squares quadratic surface (Wood 1996, Evans 1979 both cited in Jones 1998).	Non-weighted 3rd order finite differences; 8 neighbouring cells as input; According to Florinsky (1998) Sharpnack and Akin (1969) proposed formulas for f_x and f_y identical to Evans-Young.
Maximum downward gradient	Travis et al. (1975); alternatively: Maximum downhill slope attributed to O'Callaghan and Mark (1984) by Zhou and Liu (2004)		Gradient is estimated from steepest drop to neighbouring cell, "worst case slope" (Travis et al. 1975: 13) e.g. for slope stability analyses.
Evans-Young	Young (1978), Evans (1979); sometimes to Sharpnack and Akin (1969)		Fitting of a 2nd order polynomial; 3rd order finite differences; 9 cells as input
Ritter	Ritter 1987; Jones (1998) attributed the idea to Fleming and Hoffer (1979), a description to Unwin (1981) and the algorithm to Ritter (1987). However, in Fleming and Hoffer (1979) no indications about how to calculate slope gradient and aspect are found.	Diagonal Ritter; Corripio; Zevenbergen-Thorne (Jones 1998, Florinsky 1998);	2nd order finite differences; 4 neighbouring cells as input; According to Florinsky (1998) Ritter (1987) proposed formulas for f_x and f_y identical to Zevenbergen-Thorne.

Table 1 (continued).

Method name	Attributed to	Related to	Description
Horn	Horn (1981)	Sharpnack-Akin (Skidmore 1989, Carter 1992, Jones 1998); One over distance (Jones 1998)	Weighted (reciprocal of the squared distance) 3rd order finite differences; 8 neighbouring cells as input.
Diagonal Ritter			Essentially the Ritter method with apparent gradients calculated at an angle of 45° to grid directions (Jones 1998); 4 neighbouring cells as input.
One over distance	According to Jones (1998) described by Unwin (1981)	Horn (Jones 1998)	Similar to Horn, but with different weighting (reciprocal of the distance; see method name); 3rd order finite differences; 8 neighbouring cells as input.
Zevenbergen-Thorne	Zevenbergen and Thorne (1987)	same as Moore (Schmidt et al. 2003); partial derivatives identical with Evans-Young (Guth 1995, Evans and Cox 1999); "novel derivation" of Ritter (Jones 1998)	Partial 4th order surface passing through all nine cells.
Moore	Moore et al. (1993a,b)	same as Zevenbergen-Thorne (Schmidt et al. 2003)	
Shary	Shary (1995)		Similar to Evans-Young, but constraining polynomial to pass through the centre cell; probably identical to constrained quadratic surface method; f_x, f_y, f_{xy} identical to Evans-Young.
Constrained quadratic surface	Wood (1996)		2nd order polynomial surface passing through centre cell.
Simple	Jones (1998)		f_x and f_y are calculated from two elevation values respectively, only: 1st order finite differences; 3 cells as input.
Corripio	Corripio (2003)	Ritter; Diagonal Ritter	Vector-based gradient and aspect from four elevation values. Differing from Ritter in the selection of points and calculation.

The emergence of diverse algorithms to compute slope gradient and aspect (and sometimes curvatures) triggered studies which compared their performances. This was usually done by comparing results to various reference values such as hand measurements, field measurements and values obtained from real or artificial reference DEMs (Florinsky 1998). Carter (1992) used mathematically defined, uniformly sloping and uniformly oriented surfaces to investigate the influence of elevation precision and to compare the “conventional” computation (Ritter method), the Horn method and the Sharpnack-Akin/Evans-Young method. Both, the Horn and the Sharpnack-Akin/Evans-Young method yielded better results (halving RMSE for slope gradient) than the Ritter method. Carter (1992), however pointed out that averaging over larger areas (i.e. inclusion of 8 instead of 4 elevation values) will eliminate fine details. The same argument was presented by Guth (1995), who compared six gradient and aspect algorithms using real-world DEMs and computing correlation matrices for gradient and aspect, with lowest correlation coefficients being 0.898 and 0.579, respectively. However, despite high correlation for gradient, different methods may yield quite different estimates especially in neighbourhoods with changes in gradient. In neighbourhoods approximating a plane, however, algorithms tend to agree. According to Guth (1995) extreme slope values may be more relevant than smoothed, artificial values, especially in applications like cross-country mobility analysis.

Jones (1998) and Zhou and Liu (2004) more realistically than Carter (1992) used curved synthetic surfaces for obtaining reference values. The eight algorithms tested by Jones (1998) were the three in Carter (1992) and additionally the one over distance method, constrained quadratic surface method, diagonal Ritter method, simple method, and maximum downward gradient method. He found identical results for the constrained quadratic surface and the Sharpnack-Akin method. Jones assumed that any method fitting quadratic surfaces with least-squares gives results for first derivates identical to the Sharpnack-Akin method. However, the latter is not able to compute second derivatives. The ranking of the methods based on RMSE was identical for both gradient and aspect; from ‘best’ to ‘worst’: Ritter, Horn, one over distance, Sharpnack-Akin, constrained quadratic surface, diagonal Ritter, simple method and maximum downward gradient. However, the clarity of these results varied both with cellsize and with exposition (in the case of gradient). While the ‘best’ method employs 4 neighbouring cells, the next three methods use 8 neighbouring cells. Jones (1998) regarded the fact that with diagonal Ritter a method using 4 neighbouring cells ranked fourth as not contradictory, since due to the rotation of the Ritter method the footprint of the method is enlarged.

Zhou and Liu (2004) found that algorithms showed greater differences in RMSE for higher precision. For rotated surfaces Zhou and Liu (2004) described third-order finite differences algorithms (such as Sharpnack-Akin/Evans-Young, Horn and One over distance) as more sensitive to grid directions than, for example, the simple method or second-order finite differences methods like Zevenbergen-Thorne and Ritter. Corripio (2003) compared his own approach (ibid.) with the algorithm implemented in ESRIs ArcGIS (the Horn method). Though both algorithms underestimated gradient for a synthetic surface, the Corripio method gave smaller RMSE and less dispersion than the Horn method especially in gentler sloping areas.

The practice of comparing calculated values of derivatives with so-termed 'reference' values was criticised by Florinsky (1998). He instead compared different methods based on the RMSE of the partial derivatives they yield. From his studies Florinsky concluded that the Evans-Young method is the most precise for estimating partial derivatives but pointed out, that while the method is least affected by elevation errors, it does not need to represent "elevation reality" best. Other than the above studies, Schmidt et al. (2003) compared the Evans-Young method, the Zevenbergen-Thorne method and the Shary method based on the calculation of second derivatives like profile, plan and tangential curvature on a synthetic surface and on real-world DEMs. As can be expected from their similarity, results for the Evans-Young and the Shary methods were more similar than those of the Zevenbergen-Thorne method. While the overall pattern and the tendencies of curvatures were consistent among the algorithms (which is important for landform element classification), actual curvature values, the sensitivity of the algorithms to local variations and DEM cell size varied. The Zevenbergen-Thorne (partial quartic) method was especially sensitive, supporting findings by Florinsky (1998).

From a data viewpoint, Schneider (2001a,b) highlighted shortcomings of the raster data model which is predominant in digital terrain modelling and advocated a continuous, phenomenon-based specification of surfaces. The derivation of terrain parameters via the construction of a (implicit) topographic surface by any of the algorithms presented above introduces uncertainty which Schneider (2001a) termed *model uncertainty*. This point is adopted by Hugentobler (2004) who discussed and further developed ways of representing terrain continuously. However, the raster data model continues to be by far the most prominent in digital terrain modelling.

2.2.2 Resolution sensitivity[1]

Along with research about terrain parameter algorithms and the exploration of new DEM data sources (see Section 1.3) there was growing interest in the sensitivity of these algorithms to horizontal and vertical resolution. The results of this research led Longley et al. (2001: 290) to the statement, that “slope is a function of resolution” and that it makes only sense to make assertions about slope when details about the resolution it was derived at are provided.

Of all terrain parameters, slope gradient has probably seen the most attention regarding horizontal resolution. Vieux (1993) used a 30 metres DEM. On the one hand he smoothed it using 3 by 3 to 7 by 7 smoothing filters and on the other hand he downsampled the original DEM to resolutions of 210 metres. He found that both smoothing and downsampling reduce the spatial variability of the DEM, the derived gradient and also the mean gradient. However, the latter effect was more pronounced in the smoothed DEMs, most probably because of the downsampling method applied. Other authors – for example, Gao (1997; studying resolutions of 10–60 metres), Zhang et al. (1999; 20–2,000 metres, 30″ to 32′), Thompson et al. (2001; 10–30 metres), Claessens et al. (2005; 10–100 metres) – using various algorithms, noted a loss of steep slopes and shift to lower gradient values, when resolution was coarsened. Gao (1997) found that for coarser resolutions intermediate gradient values become dominant. However, in Thompson et al. (2001) the difference in the mean of gradient distributions was not statistically significant.

Zhou and Liu (2004) found that for gradient and aspect computations the error introduced by the algorithm is positively proportional to DEM resolution, whereas the influence of DEM error on the results is negatively proportional to DEM resolution. Hengl (2006) presented and exemplified heuristics to choose an appropriate grid resolution between the finest and the coarsest legible grid resolution for terrain modelling.

Also, because of its widespread use in soil-landscape and hydrologic modelling (see Section 2.3.2 on the term *soil-landscape modelling*) the secondary terrain parameter topographic wetness index (TWI; equation 1) and besides gradient its second constituent, specific catchment area, have received much attention. Early studies by Zhang and Montgomery (1994; resolutions of 2-90 metres) and Wolock and Price (1994: 30 metres and 90 metres) showed an impact of resolution on specific catchment area (SCA) and TWI. Zhang and Montgomery (1994) found that coarser resolutions introduce a bias emphasising

[1] This section is partly based on Straumann and Purves (2007).

larger SCA, with resolution affecting minimum, mean, variance and skew (but not maximum) of TWI distribution. Coarser resolutions shift the TWI and all afore-mentioned properties of the TWI distribution towards higher values (Wolock and Price 1994).

Bruneau et al. (1995) and Saulnier et al. (1997) reported a change in the shape of TWI distribution that may affect model runs within the semi-distributed hydrological model Topmodel (Beven and Kirkby 1979). This effect was suggested to be due to "differing effects on the two variables used in determining the topographic index" (ibid: 74). Thompson et al. (2001; 10–30 metres) and Claessens et al. (2005; 10–100 metres) investigated resolution sensitivity of gradient and SCA and confirmed previous studies. Claessens et al. (2005: 468) state that minimum SCA increases with coarsening resolution, since it is directly linked to resolution by the division of the upslope area by contour length.

Lane et al. (2004) were the first to compute TWI from, and use Topmodel with, high resolution (2 metres) LiDAR data. They found that within the Topmodel framework there were saturated catchment parts not connected with the stream network. This was due to low TWI values in between which persisted even after large amounts of precipitation. In our study (Straumann and Purves 2007) we used high-resolution LiDAR data, as well, to examine the implications such data have on derived terrain parameters (two versions of gradient, SCA and TWI) from a statistical and from a spatial viewpoint. We put forward the distinction between *nominal resolution* of a (raster) DEM (the cell size) and its *real resolution* (i.e. the finest resolution the sampling density of the raw data or a sampling scheme sensibly supports). The nominal and real resolutions of previous studies were specified and characterised (ibid: 91). By using dense LiDAR data to derive DEMs at 2.5 metres to 40 metres resolution, we ensured that the real resolution of each dataset is finer than the nominal resolution. In the statistical examination various trends in the distributions of gradient, SCA and TWI were found; usually in accordance with previous literature. However, extremely low (down to negative) TWI values were for the first time reported, for the finest resolutions at steepest locations. The occurrence of these values was explained and partly attributed to the high real resolution of the data used and to the terrain characteristics in the study area.

Spatially, our analysis found significant differences in the pattern of the terrain parameters with coarser resolutions blurring flow-routing hill-slope features (Fig. 4) and a property of the multiple flow direction algorithm we termed flow path or channel widening (Fig. 5; cf. also Desmet and Govers 1996, Wilson et al. 2000: 134).

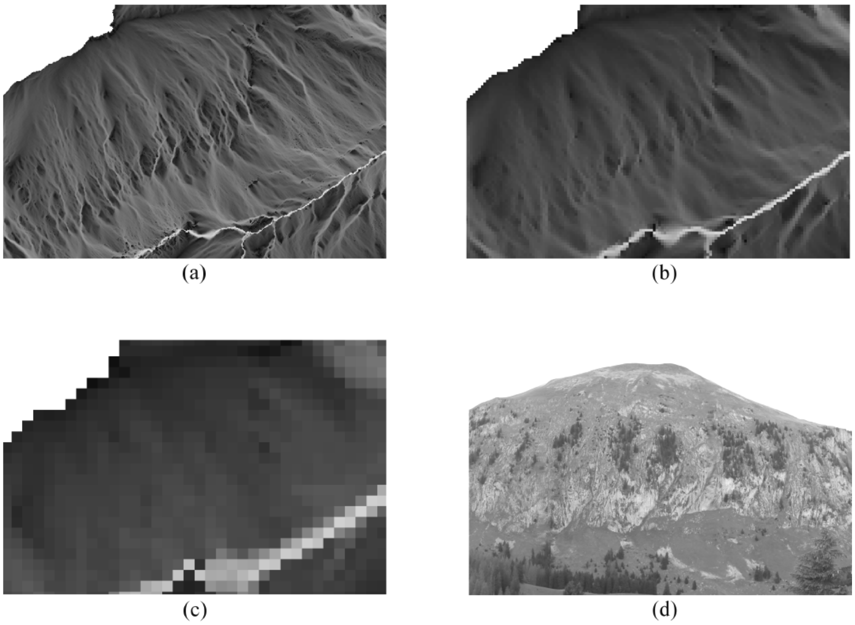


Fig. 4 Close-up view of specific catchment area at (a) 2.5 metres, (b) 10 metres, (c) 40 metres resolution; (d) photograph of the situation. (Straumann and Purves 2007).

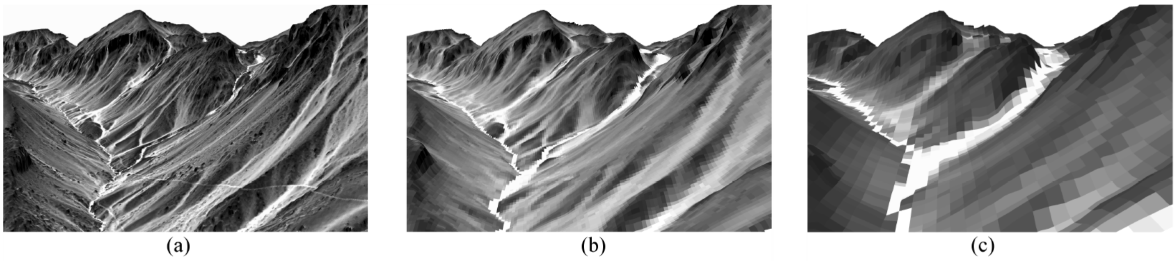


Fig. 5: Perspective view of TWI at (a) 2.5 metres, (b) 10 metres and (c) 40 metres resolution (Straumann and Purves 2007).

Both, statistical shifts of terrain parameter values and changes in the spatial arrangement of values can affect, of course, concrete implementations (like Topmodel for TWI) but also other applications producing spatial assertions from topographic parameters, such as landform modelling studies employing TWI as an input factor to classification (e.g. Irvin et al. 1997, MacMillan et al. 2000, Burrough et al. 2000). Thus, attention to resolution and scaling issues is important in the whole of digital terrain modelling. Also the inherent multi-scale nature of land surface form is more and more acknowledged. Both developments set the stage for the advent and popularity of multi-scale landform element modelling. There exists a branch of algorithms which incorporate analysis of land surface form at multiple scales (these scales not necessarily being operationalised as raster cell sizes, however). The following section (and specifically, Section 2.3.4) will detail such approaches.

2.3 Landform and landform element modelling

The origins of surface morphometry – the analysis and measurement of surface form – date back to the mid-nineteenth century (Wood 1996: 2). Some early works include those by Cayley (1859) and Maxwell (1870) and ever since the description of land in terms of its surface form has remained an important topic and aim of geomorphology. Evans (1972: 18) introduced the notions of *general* and *specific geomorphology*, defining the former as the "measurement and analysis of landform which are applicable to any continuous rough surface" and the latter as the "measurement and analysis of specific landforms (...) which can be separated from adjacent parts of the land surface".

Wood (1996) describes two renaissance-phases in the field of surface morphometry. The first one occurred in the 1970s with the advent of computing technology. In 1996, according to Wood, the field was experiencing the second renaissance characterised by the "widespread availability of Geographical Information Systems". This seems still valid. GIS enable us to handle and analyse large amounts of spatial data in a single framework (Burrough et al. 2000) and features various powerful algorithms to compute simple terrain derivatives and more complex surface properties from (usually gridded) elevation data (MacMillan et al. 2000; see also Section 2.2).

The study of surface form has always been closely linked to research in soil science. Soil scientists, geographers and scientist from other fields used and use characterisations of land surface form to analyse and infer, for instance, large-scale terrain characteristics (Hammond 1954), soil properties, soil distribution and redistribution, the presence of bundles of geomorphic processes and movement and distribution of water (Pennock et al. 1987). The application of landform modelling in soil science will be touched upon briefly in Section 2.3.2.

This chapter reviews aims, underlying paradigms, methods and innovations in the field of landform (element) modelling. It is structured as follows. First, terms used in the research field to be reviewed are consolidated. Then soil-landform modelling is introduced and briefly reviewed. Subsequently innovations and paradigm shifts, such as the adoption of a fuzzy perspective along with new classification approaches, object-orientation and analyses at multiple spatial scales are explored. Following an inventory of such methodologies some approaches dealing with landforms rather than landform elements will be reviewed.

2.3.1 Definitions: Landform and landform element

Landform. The term *landform* is defined in at least two different ways. These are reflected in two definitions for the term in the Oxford English Dictionary (OED 2009):

- a landscape of any particular kind
- a physical feature of the earth's surface such as a hill, plain, cirque, or alluvial fan

Along with the first definition goes that by Whittow (2000): "the morphology and character of the land surface that results from the interaction of physical processes (...) and crustal movements with the geology of the surface layers of the Earth's crust." Both these definitions are essentially field-based (with respect to what is termed the *field-object dichotomy* in geographic information science; see Section 3.1). Here, *landform* could be transcribed as "land surface character in terms of form". However, OED's definition along these lines is marked as obsolete. *Landform* is much more often used in the second (object-based) meaning. OED's definition, however, is not very informative. The McGraw-Hill Dictionary of Earth Science (2003) defines landforms as "all the physical, recognizable, naturally formed features of land, having a characteristic shape". Even more detailed is the definition by the U.S. Department of Agriculture (2005): "Any physical, recognizable form or feature on the earth's surface, having a characteristic shape, internal composition, and produced by natural causes; a distinct individual produced by a set of processes. Landforms can span a large size (e.g., *dune* encompasses a number of feature [sic] including *parabolic dune*, which is tens-of-meters across and *seif dune*, which can be up to a 100 kilometers across). Landforms provide an empirical description of the earth's surface features." Here, landforms have both a characteristic shape and a characteristic internal composition. Also, landforms are formed by natural (rather than anthropogenic) processes.

In this research the object-based view of the term landform is adopted, thereby denoting physical, natural features of the earth's surface which have a recognisable shape and composition. Most landforms are larger than most landform elements; naturally, larger than their own constituting landform elements.

Landform elements. There is an abundance of terms to denote somewhat homogeneous regions with regard to surface shape, which are usually smaller than landforms and can be considered building blocks of the latter. The terms *landform element* (Speight 1968, Bolongaro-Crevenna et al. 2005), *landform unit* (Moreno et al. 2004, Schmidt and Hewitt

2004), *relief unit* and *landscape type* (Romstad 2001), *land element* (Schmidt and Hewitt 2004), *land component* (Dymond et al. 1995), *landscape element* (Fels and Matson 1996), *landscape facet* (Burrough et al. 2000) and *landform facet* (MacMillan et al. 2000) can be used synonymously, however we prefer *landform element* over the others. The term *soil-landscape unit* (de Bruin and Stein 1998) puts some emphasis on soil forming factors but still more or less equates *landform element*. Also more exotic terms such as *topo-climatic classes* (Burrough et al. 2001) and *morpho-units* (Adediran et al. 2004) are effectively synonyms.

Wood's (1996) morphometric features can be understood as landform elements, as well. However, while in most GIS these morphometric features are often analysed in a 3 by 3 neighbourhood on a very finely resolved DEM, the morphometric features can also be extracted with windows for implicit surface fitting of considerable extent (LandSerf s.a.). Thus, it is problematic to directly equate these (in the former case depending on the context very small and in the latter case rather large) morphometric features with landform elements.

Speight (1968) defined landform elements as "zones of a hillslope with a defined range of surface morphological attributes" (cited in Pennock et al. 1987: 301). In the remainder of this thesis and using Speight's (1968) definition we will use the term *landform elements* to denote smaller entities which complex landforms are usually composed of. Generally, these are defined by similar ranges for various terrain parameters such as gradient, aspect, plan and profile curvature.

As mentioned in Sections 2.1.4 and 2.1.6 landforms and landform elements depend to varying degrees on human fiat and are often conceptually vague. Thus, the idea of being able to unambiguously dissect a landscape into distinct landforms and landform elements is necessarily a simplification.

2.3.2 Origins of landform element modelling

One of the origins (the most influential one) of landform element modelling lies in what is termed *soil-landscape modelling*. In 1941, Jenny (1994; unaltered reprint of the work from 1941) emphasised the role of topography in soil formation and criticised that the current approaches acknowledged topography primarily for its role in runoff formation and thus in removal and destruction of soil. However, already by 1948, the New Zealand Genetic Soil

Classification included landform as an environmental factor in soil formation (Hewitt 1992). According to Pennock et al. (1987), Aandahl (1948) is usually credited as one of the first to acknowledge the influence plan and profile curvature exert on soil properties. However, most researchers focused only on profile curvature. Examples of this kind of approaches are Ruhe's (1960) classification of slopes into summits, shoulders, backslopes, footslopes and toeslopes and the one by Dalrymple et al. (1968) encompassing nine profile form units (Pennock et al. 1987).

Troeh (1965) then put forward four landform concavity-convexity classes for the quantitative treatment of landforms (Fig. 6) which combined plan and profile curvature. These were later picked up by Huggett (1975). Milne (1936, after Huggett 1975) introduced the concept of the *catena* as a framework for soil formation on hilly terrain. The catena concept has led to the insight, that the soils of a landscape mutually influence their formation and has thus emphasised the importance of topography in the soil forming process. Landform concavity-convexity classes were related to typical expression of patterns of flowlines by Huggett (1975). Latter patterns both in lateral and vertical directions influence the distribution of water and hence erosion, transport and deposition of soil material. Subsequently, the emergence of the idea of soil-landscape modelling, namely that there is a connection between the landform pattern in a certain region and the distribution of soil types, has spurred many applications of digital terrain modelling in soil science.

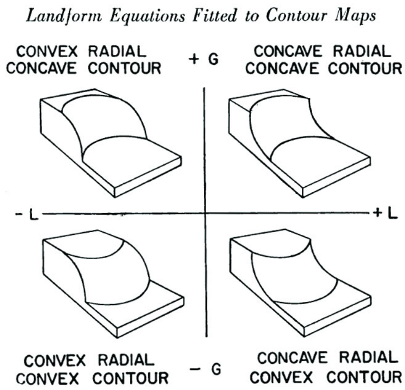


Fig. 6: Troeh's four combinations of concavity and convexity of landforms (Troeh 1965).

Within soil-landscape modelling there are basically two kinds of approaches. The first kind involves the direct examination of the relationships between terrain parameters and soil properties. Such an approach was taken by, for example, Oliver and Webster (1986), Odeh et al. (1991), Thompson et al. (2001) and Moore et al. (1993a: 444; 1993b). For instance, Moore et al. investigated the supposed connection using multiple regression techniques between terrain parameters and soil properties.

It is the second approach which has much driven and influenced the classification of landform elements. It classifies a region into landform elements in an attempt to stratify the soils of a study area, to characterise the distribution of water (Pennock et al. 1987: 299), soil properties or types and/or to aid sampling of soil properties (e.g. Odeh et al. 1992, Pennock et al. 1994, Irvin et al. 1995, 1997, Fels and Matson 1996, de Bruin and Stein 1998, Dobos et al. 2000, Pennock and Corre 2001, Pennock 2003, Scull et al. 2005, Murphy et al. 2005). Alternatively, rather than inferring soil types or characteristics from landform elements classifications, McBratney et al. (1992), Dobermann and Oberthür (1997) and Franssen et al. (1997) directly classify measured soil characteristics.

For an encompassing review of techniques for soil mapping (including also statistical and remote sensing approaches) refer to Scull et al. (2003), for a history of concepts related to soil classification and mapping with a focus on fuzziness refer to Burrough et al. (1997).

Clearly, the classification of landform elements has multiple applications and is not confined to soil science – although here soil science is considered an important enough driver to deserve a dedicated brief section. Apart from soil science, landform element modelling has become a task on its own, i.e. it was pursued with the goal of earth surface form characterisation. This brought other motivations into the field of landform element classification which were independent from the soil-landscape modelling paradigm. Landform analysis is of interest for the description of a landscape in terms of elements it contains (Brown et al. 1998; Romstad 2001). Examples of this approach are the studies by Brabyn (1998), Darra et al. (2003), Fisher et al. (2004), Adediran et al. (2004) and Bolongaro-Crevenna et al. (2005). Further, purposes of landform element classification include (after Brown et al. 1998): information on landscape genesis, the inference of properties not directly observed and frame of reference for the limits for extrapolation of observed processes, assessment of land suitability (cf. Speight 1977), understanding and mapping of groundwater recharge, aquifer vulnerability to contamination (e.g. Fels and Matson 1996 and Matson and Fels 1996) and other hydrological or ecological properties or processes (cf. Burrough et al. 2000, Schmidt and Hewitt 2004; e.g. Burrough et al. 2001, Park and van de Giesen 2004), defining management units for precision farming (MacMillan et al. 2000), delineating regions of governmental funding (Darra et al. 2003) or assessing and mitigating natural hazards such as landslides (Pike 1988).

In what follows the focus will thus be broadened to also encompass such approaches and their methodological advancements.

2.3.3 Approaches to landform element classification

There are two general classification methodologies. One is called *unsupervised classification*, the other *supervised classification*. Both of them are often treated in remote sensing literature, since remote sensing traditionally occupied itself with classification. In the following explanations we will refer to such a piece of literature (Richards 1993).

Unsupervised classification. Unsupervised classification assigns pixels in an image (or in a DEM) to classes "without the user having foreknowledge of the existence or names of those classes" (Richards 1993: 85) and "without referencing existing classification systems" (Irvin et al. 1997: 142). Implementations of this approach are clustering methods that define both the set of classes and the assignment of each considered element into one of the classes. Studies in landform elements classification predominantly use the *ISODATA* and *fuzzy c-means* clustering algorithms (fuzzy c-means is the same as fuzzy k-means, both terms appear equally often; fuzziness and related approaches will be treated in Section 2.3.4). Both algorithms are derivates of the *k-means* algorithm and aim to form groups with high internal similarity from multivariate data. ISODATA (Ball and Hall 1965) is a crisp clustering algorithm that allows the merging and splitting of clusters during the clustering process (cf. Jain et al. 1999). Fuzzy c-means (Bezdek et al. 1984) is an application of Zadeh's (1965) fuzzy set theory to clustering wherein objects can be partial members of several clusters depending on their location in attribute space. For more in-detail reviews of clustering methodologies and algorithms refer to Jain et al. (1999) and Xu and Wunsch (2005).

In the clustering approach, the user must identify the found classes *a posteriori* referring to maps, ground truth or expert knowledge, or, depending upon the application, the user is satisfied with the classes themselves without putting a label on them (e.g. de Bruin and Stein (1998) employing fuzzy c-means clustering abstain from explicitly naming the four classes they derived). Prototypical studies with unsupervised classification approaches were undertaken by, for instance, Irvin et al. (1997), de Bruin and Stein (1998) and Burrough et al. (2000). Irvin et al. (1997) evaluate two methods for deriving landform elements (one crisp, one fuzzy) with respect to each other and to a manual delineation of landform elements. Both methods involve clustering of input variables like slope gradient, profile and tangential curvature, solar insolation and TWI. Pike (2000a) identifies six European terrain types from a cluster analysis on six terrain parameters. Iwahashi and Pike (2007) use slope gradient, local convexity and surface texture for deriving globally 16 topographic types.

Since in unsupervised classification classified elements cannot be identified *a priori*, the selection of input variables has to be made cautiously, for this step will essentially decide what will be classified how: "Unsupervised classification methods may identify a number and composition of classes that do not correspond to preconceived notions of the makeup of the landscape. In terrain analysis, classes may be produced that do not fall within classic landform boundaries such as those of Ruhe and Walker (1968)" (Irvin et al. 1997: 141p). An important question poses itself also regarding the number of classes. In an interesting approach to the problem, Irvin et al. (1997) determine the optimal number of classes for each approach through expert knowledge with the guidance of the fuzzy performance index (FPI) and the normalised classification entropy (NCE) (Odeh et al. 1992) as objective functions. Burrough et al. (2000) apply a fuzzy c-means classification for which they use the scaled partition coefficient and classification entropy to judge the optimum number of classes.

Supervised classification. Supervised classification requires the operator to define the classes beforehand, which can be done in two ways: Either thresholds or class characteristics can be obtained from experience, expert judgement and literature, or from samples – so-called training areas – which are manually designated and which stand prototypically for a class. The algorithm will subsequently allocate the not yet classified pixels or cells to these classes. However, in the field of landform classification this is seldom done. More commonly, users of the supervised approach refer to historical, "sensibly" assumed or conventional classification schemes for threshold values. Using these threshold values classifications involving decision trees or, even simpler, parallelepiped classifier are usually set up (Fig. 7). Alternatives to these are, for example, the maximum-likelihood classifier or the minimum-distance classifier.

Pennock et al. (1987), Dikau (1988, 1989), MacMillan et al. (2000), Wood (1996) and Schmidt and Hewitt (2004) are the most prominent authors of common classification schemes of landform elements. These schemes are quite similar, often relying on gradient and plan and profile curvature. For example, in their 1987 study, Pennock et al. classified a hummocky landscape into seven landform element classes which were in fact a further subdivided version of the scheme suggested by Ruhe (1960): convergent/divergent shoulders, convergent/divergent backslopes, convergent/divergent footslopes and level elements (Fig. 8).

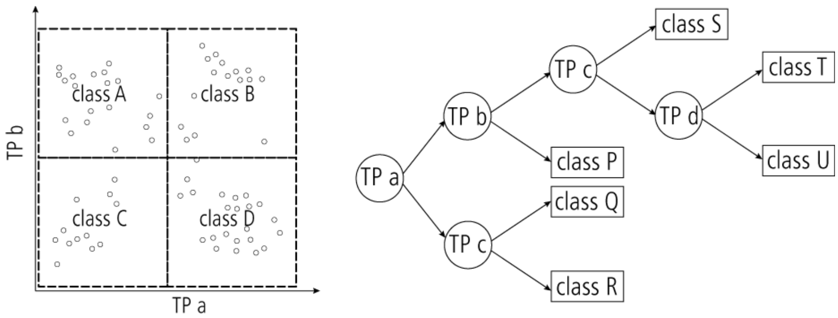


Fig. 7: Parallelepiped classifier segmenting the terrain parameter (TP) space (left), decision tree or hierarchical classification based on thresholding of terrain parameters (TP) (right).

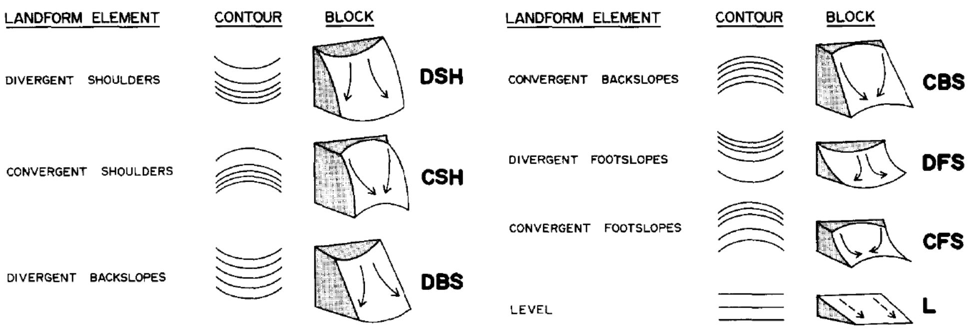


Fig. 8: Landform element classes of Pennock et al. (adapted from Pennock et al. 1987: 303).

Pennock et al. (1987) suggested that incorporating the different landform elements into, for example, sampling schemes would be beneficial. Pennock et al. (1994) extended the method to incorporate what they termed "landform element complexes". These were derived from basic landform elements through application of a filtering technique merging individual occurrences of landform elements into larger patches. The study proved the generalisation into landform element complexes to be interesting for regional studies.

Pennock and Corre (2001) and Pennock (2003) devised an eight element classification scheme including thresholding of catchment area for the "level" class yielding "high catchment level" (HCL) and "low catchment level" (LCL) classes.

Similarly to Pennock et al. (1994), Dikau (1988, 1989) proposed a hierarchic classification scheme for landform elements. The smaller elements, which are defined as relief units with homogeneous gradient, aspect and plan and profile curvature, were termed “form *facets*”. The larger “form *elements*” are relief units with homogeneity only in plan and profile curvature. Dikau suggested a classification scheme for these which is similar to that of Pennock et al. (1987), but features two more classes which are planar in plan direction and six aggregate classes (column- and row-wise; Fig. 9). Notably, Dikau (1989) also introduced an arbitrary threshold value of 600 metres to be used with the curvatures in his classification scheme, which later has sometimes been re-used by other researchers (presumably, because of a severe lack of other indicative numbers). Dikau’s classification was also applied by, for example, Moreno et al. (2004) and Reuter et al. (2006), however, including again Pennock’s HCL and LCL classes.

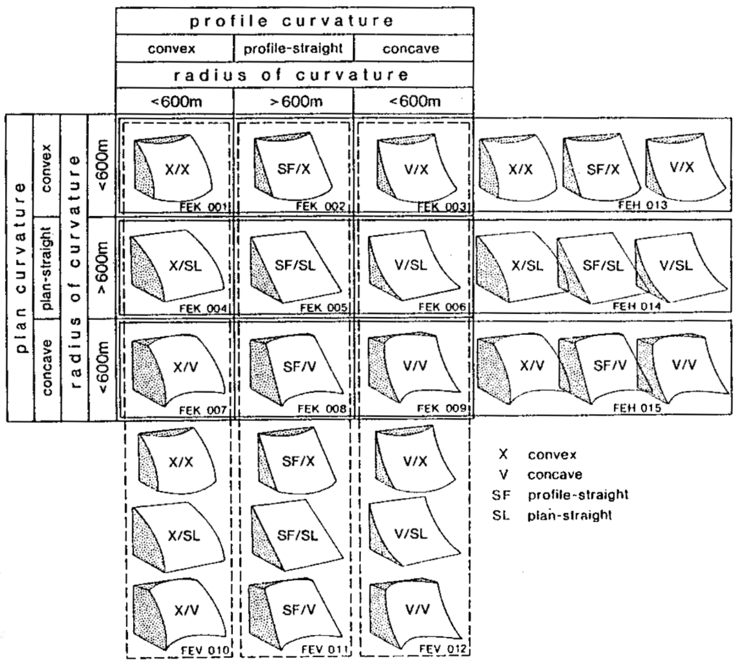


Fig. 9: Classification of form elements after Dikau (1989).

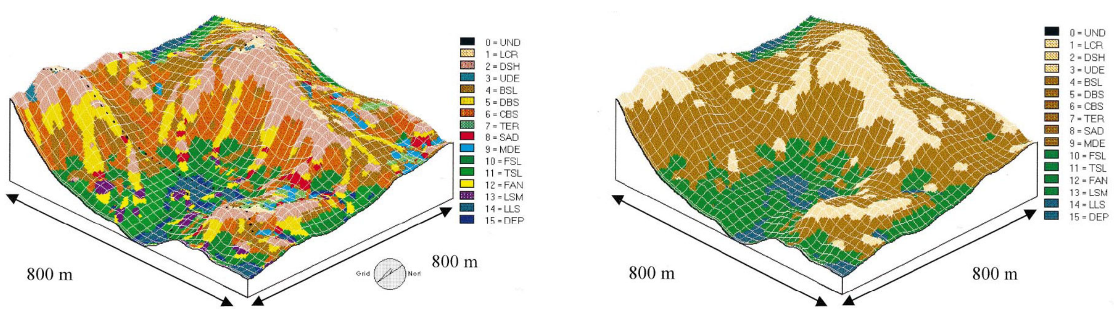


Fig. 10: Threedimensional view of initial and generalised classification results (MacMillan et al. 2000: 101).

For a classification aimed at supporting precision farming, MacMillan et al. (2000) introduced a set of innovative terrain parameters to landform element classification and proposed a 15 element landform elements classification scheme including “conceptual entities similar to six of the original seven landform units of Pennock et al.” but replacing Pennock’s level class with “six separate units to differentiate level areas and depressions in upper, mid and lower landscape positions respectively”. Additionally, the classification of MacMillan et al. encompassed two classes (mid- and lower-slope) that are planar in across-slope direction and a lower-slope mound class that morphologically resembles a divergent shoulder but is located in low landscape positions (footslopes and toeslopes). The 15 classes and their characteristics were assigned using expert judgement and yield a very complex image (Fig. 10, left), which was simplified using a post-classification filter which aggregated the 15 classes into four to render the result clearer (Fig. 10, right).

In some ways, the classification into six morphometric features (pit, peak, pass, ridge, channel, plane) as detailed by Wood (1996), is a generalisation of the above (mostly soil-related) approaches. Wood’s classification scheme does not only apply plan and profile curvature with gradient but relies on cross-sectional, minimum and maximum curvature along with gradient for classification. The latter two curvatures are used in regions with no or little gradient, where cross-sectional curvature makes little sense. Additionally, Wood (1996: 117) limits pits, peaks and passes to locations of zero gradient (at some scale) thereby eliminating spurious classifications of these features.

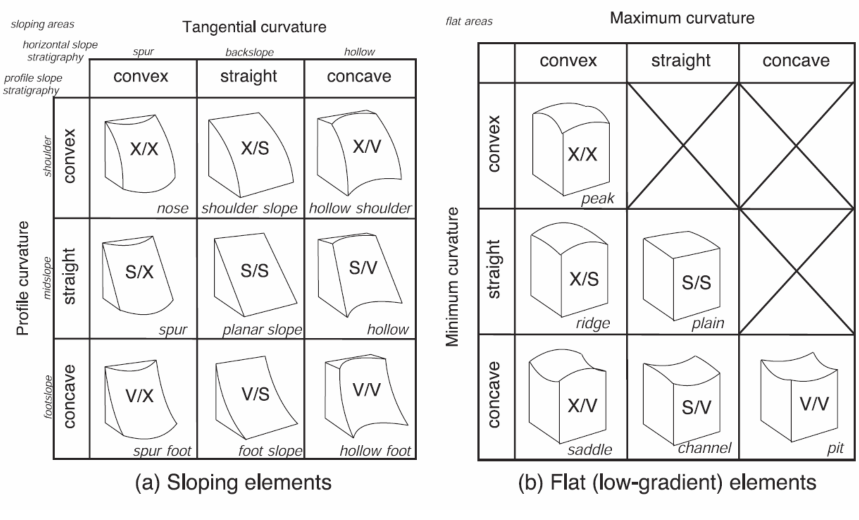


Fig. 11: The 15 fundamental local landform elements of Schmidt and Hewitt (2004: 247).

Bolongaro-Crevenna et al. (2005) applied Wood's classification scheme to characterise different regions through their differing contents of morphometric features using double ternary diagrams. In most cases they were successful in distinguishing different large-scale landforms (such as volcanoes) with statistical significance.

Schmidt and Hewitt (2004) expanded the six morphometric features into 15 classes, separated into sloping (based on tangential and profile curvature) and flat elements (based on minimum and maximum curvature) (Fig. 11). Their scheme is a combination of that by Dikau (1989) and that by Wood (1996). Most interestingly, they combined the landform element classification with a "higher scale landscape position model" which distinguished between "hill", "hillslope" and "valley". Based on their vertical position in the landscape landform elements were then subject to re-allocation resulting in a more coherent and richer classification.

Besides the above widely known and popular classification schemes, there are other approaches to landform elements employing, for instance, decision trees or supervised classification with training data rather than values derived from expert knowledge or literature. For example, Fels (1995) and Fels and Matson (1996) devised a classification scheme for North Carolina which was based on a decision tree employing slope gradient and a landscape position index computed on a certain predefined neighbourhood. The method needed many parameters to be tuned, which was achieved by iterative visualisation and re-classification.

As to supervised classifications employing only training data there is much less literature. Hengl and Rossiter (2003) proposed an approach to extrapolate existing aerial photo interpretations aimed at soil investigations using a maximum likelihood classifier on training data sets. Similarly, Brown et al. (1998) applied maximum likelihood classification and artificial neural networks to classify features of glaciated landscapes relying on various terrain parameters. While the neural network approach detected more detail, the overall classification agreement was better for the maximum likelihood classifier. Scott and Pinter (2003) implemented a somewhat specialised algorithm using training areas. They extracted coastal terraces by iteratively delineating terrace candidates from gradient and relief rasters applying a scheme of arbitrarily chosen thresholds and neighbourhood sizes. Each resulting raster was compared to manually mapped coastal terraces on western Santa Cruz Island to find the best extraction technique. That technique was then applied to other nearby areas.

Another strand of approaches is based on region-growing rather than cell-wise classification into landform elements. Because of the adoption of a threshold criterion which is known *a priori*, these approaches can justly be subsumed within the supervised classification methodology. A region-growing approach was adopted by Miliaresis and Argialas (1999) who delineated mountains and basins and assigned unclassified pixels to a piedmont class. Seed pixels were chosen based on higher-than-average runoff (downslope for basins and upslope for mountains). The threshold for region growing was taken from literature. A similar methodology was applied to the extraction of alluvial fans (Miliaresis and Argialas 2002). In both examples the authors also defined training areas to test or derive threshold values from the literature, thereby to some degree combining the two approaches to class definition in supervised classification. Miliaresis and Argialas (2002) and Miliaresis (2006) took the approach one step further through complementing the segmentation of mountains with a k-means classification of the derived objects based upon the distribution of terrain parameters within their outline.

With those latter two publications Miliaresis and Argialas (or the former alone) come quite close to what is termed object-based (rather than pixel-based) classification in remote sensing. In such approaches, an area is first segmented into image objects which are subsequently classified using their internal characteristics. Examples of such approaches in landform element classification were implemented by Giles and Franklin (1998), van Asselen and Seijmonsbergen (2006) and Drăguţ and Blaschke (2006).

Giles and Franklin (1998) and Giles (1998) implemented a segmentation algorithm which breaks downslope profiles on points of break of slope. The resulting "slope units" are then described by terrain, shape and spectral parameters. Using linear discriminant analysis the classification was trained and tested and correlated variables were excluded. In the southwest Yukon Territory in Canada, Giles (and Franklin) were capable of classifying slope units into ten classes with a discrimination accuracy of 90%. Metternicht et al. (2005) implemented parts of the slope unit scheme by Speight (1990) as a simple, customised supervised classification. For splitting the slope class they used a modification of the algorithm by Giles and Franklin (1998). However, their aim was not in a strict sense a subsequent object-based classification, but rather an allocation of slope units to slope unit classes based on topology. The same methodology was applied by Klingseisen et al. (2008) and evaluated somewhat successfully against a photo-interpretation by an expert in soil surveys. The study by van Asselen and Seijmonsbergen (2006) was more strictly object-oriented. It involved segmentation of objects based on slope gradient and subsequent classification of these objects using expert knowledge and training areas in a supervised approach with mixed results. Drăguț and Blaschke (2006) applied proprietary software for segmenting a DEM into objects. To classify these they used a modified version of the classification scheme by Dikau (1989) where they re-allocated occurrences in four improbable landform element classes to one of the remaining five classes. Additionally they used a flat and a peak class; all these were further divided into upland, midland and lowland elements using relative elevation.

Simpler approaches were put forward by, for example, Darra et al. (2003) who proposed a classification on gradient and elevation alone or by Morgan and Lesh (2005) who tried to mimic the landform classification by Hammond (1954) (something which was also attempted by Brabyn (1998)). Blaszczynski (1997) devised a surprisingly un-noisy classification into convex, concave and flat areas only by looking at elevation differences of the central cell to its eight neighbours. The level of detail could be affected by choosing a different neighbourhood size (this makes the method a simple multi-scale approach).

Other studies have occupied themselves with the question of how DEM characteristics influence landform element classifications. Effects of DEM generalisation on a landform element classification were investigated by Reuter et al. (2006) and significant impacts were found. Consequently, a non-linear optimisation method was devised which enabled extrapolation from a section of a DEM with higher information onto larger areas with only limited (generalised) information. Hengl et al. (2004) investigated the use of error reduction techniques on DEMs and how these improved classification results. Using filtering techniques and averaging terrain parameters from multiple DEM realisations they could significantly improve accuracy of a maximum likelihood classifier (Hengl and Rossiter 2003).

2.3.4 Important paradigm shifts

Incorporation of fuzziness. As was already detailed in Section 2.1.5 there are many boundaries in the realm of geographic objects which are not crisp.

For soil-landscape modelling an insightful review paper by Burrough et al. (1997) looks at development from crisp to fuzzy approaches in that field. Traditional (soil) classification methods used a crisp representation of the world assuming “a very strong equivalence between taxonomic groupings and the map polygons used to indicate the location of these soils on the ground" (Burrough et al. 1997: 116). Though at larger scales homogeneity of map polygons was assumed, at small scales it was accepted that map polygons are not pure in the sense that they exclusively contain the specified soil type. Burrough et al. (1997) date the advent of the fuzzy approach in soil science to the 1990s. This approach embraces fuzzy set theory (Zadeh 1965) by "accepting the principle that a site can belong to more than one class and the idea of partial overlap of the classes in attribute space" (Burrough et al. 1997: 121). Because of the strong links between the two fields, the same reasoning can be transferred to landform element analyses.

From a more formal perspective, crisp approaches aim to divide a sample of individuals into sets with crisp boundaries (i.e. Boolean or Cantor sets). In this perspective, an individual x is member of class A or not. Classes are exclusive: If x is a member of A it cannot simultaneously be a (partial) member of B. Consider the membership function drawn as solid line in Fig. 12. While the term 'membership function' stems from the fuzzy world, it can also be used to represent Boolean sets. In this case the membership function is restricted to 0 and 1. Assuming the indicator variable is gradient, the solid line in Fig. 12 could be a representation of a Boolean set *moderately steep*.

Fuzzy approaches to classification and clustering are based on fuzzy set theory that was first presented by Zadeh in his seminal paper in 1965. Fuzzy sets overcome some of the shortcomings of Boolean sets. A fuzzy set is "a 'class' with a continuum of grades of membership" (Zadeh 1965: 339). In fuzzy set theory an individual is not said to belong to either set A or set B; to some degree, it can belong to both sets. This fuzzy membership of an individual x to a set A is expressed as a real number $\mu_{x,A}$ in the interval [0, 1]; the higher $\mu_{x,A}$ the closer the individual x is to the central concept of set A. If $\mu_{x,A}$ is near 0, x has little similarity to the concept of A.

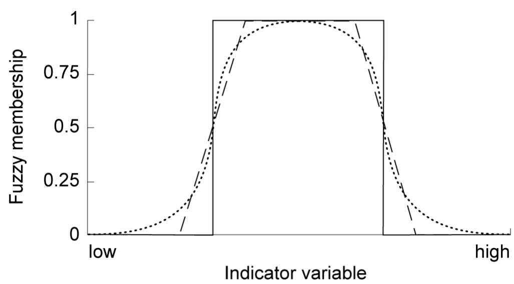


Fig. 12: Examples of membership functions.

For an example of fuzzy classification consider the membership function drawn as dashed line in Fig. 12, where the dashed membership function could be that of a fuzzy set *moder-*

ately steep. This fuzzy set can be easily converted into a Boolean set (i.e. 'hardened') with a threshold value of $\mu_{x,A}$ = 0.5. Indeed, this is relatively often done with classes resulting from fuzzy classification. The dotted line in Fig. 12 is a smoother membership function of the same set.

Fuzzy supervised classification. In supervised fuzzy classification a *semantic import* (SI) *model* is used to define membership functions for different sets (Fisher 2000b: 170pp, Burrough and McDonnell 1998: 270pp, Robinson 1988: 93, McBratney and Odeh 1997: 95, 98pp). Position and shape of these membership functions are inferred from literature or expert knowledge. In the case of landform element classification, for example, the 'classical' classification schemes by, for instance, Hammond (1954) or Pennock et al. (1987) can be 'fuzzified'.

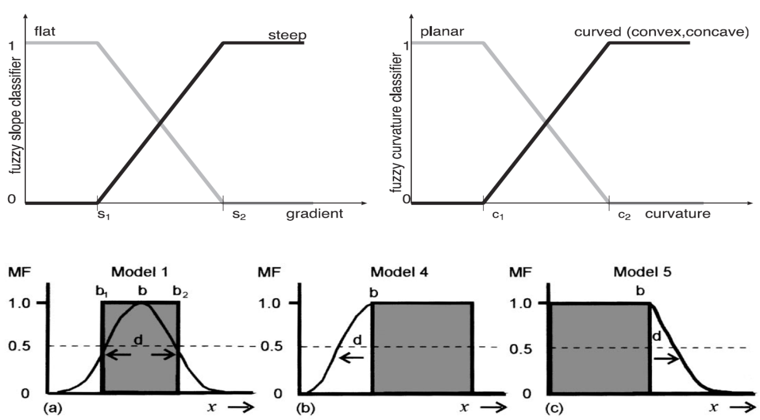


Fig. 13: Semantic import models for the terms 'steep' and 'flat', 'planar' and 'curved' (Schmidt and Hewitt 2004) (top) and semantic import models by MacMillan et al. (2000) (bottom).

As described in Section 2.3.3, Schmidt and Hewitt (2004) used a set of local landform elements that is a combination of Dikau (1989) and Wood (1996). Since the definition of terms like *flat* versus *sloped*, *straight* versus *convex* or *concave* are "subject to considerable uncertainty (fuzziness)" and "these thresholds depend on the terrain characteristics", Schmidt and Hewitt (2004: 246p) find it appropriate to substitute hard thresholds with fuzzy ones. They developed simple semantic import models for the above-mentioned terms (Fig. 13, top). Schmidt and Hewitt (2004) see the main advantage of their approach in the consideration of semantic uncertainty. They can quantify uncertainty in the classification results by the maximum membership value, the confusion index (Burrough et al. 2000: 40) or entropy values (see the shortly following sub-section on multi-scale approaches). Mac-

Millan et al. (2000) on the other hand (their complex set of 15 landform element classes has been mentioned in Section 2.3.3) used three sophisticated membership functions for their classification (Fig. 13, bottom).

Fuzzy unsupervised classification. The field of fuzzy unsupervised classification of landform elements is incorporated by approaches that mostly use the popular fuzzy c-means algorithm (Bezdek et al. 1984, McBratney and de Gruijter 1992, McBratney and Odeh 1997: 95pp). The fuzzy c-means algorithm is an implementation of the *similarity relation model* (SR; as opposed to the semantic import model). This can be described as an approach which uses pattern recognition to derive membership values from the data itself (Fisher 2000b: 174pp, Robinson 1988: 93).

Examples of applications of fuzzy c-means are the studies by Irvin et al. (1997), de Bruin and Stein (1998), Burrough et al. (2000) and Burrough et al. (2001). Irvin et al. (1997) judged the effort needed to be smaller for a crisp than for a fuzzy classification; one reason for this being that the ISODATA classification (as opposed to the fuzzy c-means classification) was implemented in a major GIS vendor's software. Irvin et al. (1997: 151) pointed out a trade-off insofar as "graphic renditions [of the crisp classification results] are easy to interpret but lack information about transition zones" and "the continuous [fuzzy] classification provides much additional information on each data point" but "the results are not as easily visualized". De Bruin and Stein (1998) found that optimising fuzzy c-means clustering could be performed for their application by examining the coefficient of determination of regressing soil characteristics on membership values. McBratney and de Gruijter (1992) modified the traditional fuzzy c-means approach by introducing an *extragrade* class which could accommodate individuals lying outside the convex hull of class centres in parameter space. Additionally, McBratney (1994) proposed a method to allocate new samples to existing fuzzy soil classes. Burrough et al. (2000) overcame limitations of applying fuzzy c-means by down-sampling the number of cells taken in consideration in the SR model using a stratified, nested sampling scheme. When the algorithm has defined the clusters, these can be used to assign class membership values to *all* raster cells. Additionally, Burrough et al. (2000; similar to Hengl et al. (2004)) dealt with uncertainty in the data and artefacts by adding a Monte Carlo simulation to the computation of the terrain parameters on which the clustering is based. Burrough et al. (2000) successfully tested the new method in two study areas and Burrough et al. (2001) further demonstrated its applicability in a paper using a 10,000 km^2 study area in Yellowstone National Park at 100 metres resolution (resulting in 1,000,000 raster cells).

An innovative approach to fuzziness was taken by Fisher et al. (2004). They interpreted multi-scale morphometric classification as fuzziness. This approach will be detailed in the next section.

Acknowledgement of the multi-scale nature of landform elements. Wood (1996: 15) mentioned Richards (1981) who highlighted a number of problems with geomorphometry, particularly that "results obtained [from geomorphological investigations] are invariably specific to the scale (...) adopted" (Richards 1981: 26). The problem of scale as perceived by Richards is twofold; as Fisher et al. (2004: 108) noted, the term denotes both the spatial extent of an investigation and the resolution at which the investigation is carried out. As early as 1972 Evans noted that many terrain parameters computed from raster DEMs are sensitive to the spatial resolution. This notion has spurred much research to verify and quantify the effects spatial resolution of DEMs has on terrain parameter computation (see Section 2.2.2).

The realisation that terrain parameters are dependent upon the resolution of the DEM led Wood (1996: 88p) to conclude that "the techniques (...) for morphometric characterisation of DEMs are all constrained by the resolution of the model. The information derived using these techniques is relevant only to the scale implied by the resolution of the DEM. Since this scale is often arbitrarily defined and not necessarily related to the scale of characterisation required, derived results may not always be appropriate." He (Woods 1996: 15) even stated that the scale issue makes "single objective classifications of landscape unfeasible" and that "it would seem ludicrous to only consider surface variation at a fixed scale when an assessment of an entire landscape is desired. Our own judgements both scientifically and 'intuitively' rely on an appreciation of landscape at a variety of scales simultaneously." (ibid: 89; cf. also Schneider 2001a,b, Schmidt and Andrew 2005).

Consider as an example the horizon line depicted in Fig. 14 where different scales of analysis come up with a different classification for the feature at hand. Rather than employing resampling of gridded DEMs for tackling the scale issue, in his PhD thesis Wood (1996) devised a methodology termed *multi-scale quadratic approximation*. This technique is essentially a generalisation of that employing a 3 by 3 window for implicit surface fitting by Evans and Young (Young 1978, Evans 1979; see Section 2.2.1 and Appendix B). It involves fitting n by n (where n is uneven) implicit surfaces to cells in a DEM using quadratic polynomials. If wished, the quadratic can be constrained to pass through the central cell, which makes the surface fitting ‘exact’. With this technique, Wood (1996) could compute terrain parameters at various scales. Fig. 15 shows cross-sectional curvature computed at four different scales draped onto a hillshaded three-dimensional representation of the DEM. Obviously, cross-sectional curvature varies dramatically with the scale of analysis.

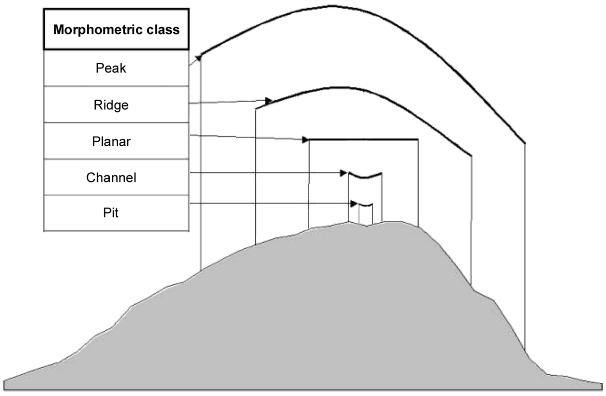


Fig. 14: Morphometric classes at a point at different scales of measurement
(adapted from Fisher et al. 2004: 109).

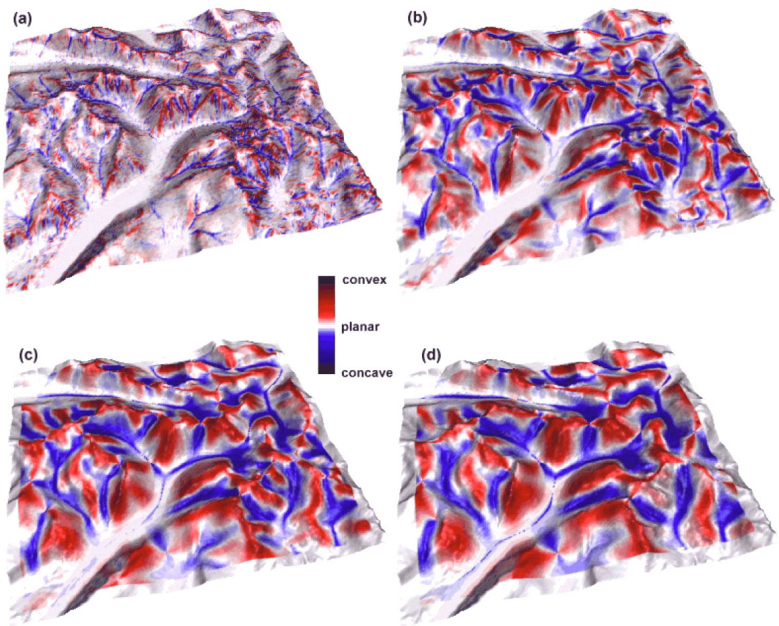


Fig. 15: Cross-sectional curvature computed at four different scales according to Wood’s methodology
(Wood 1996: 159).

“It is suggested that this scale based progression of characteristics is much more useful than a single morphometric parameter or classification. It provides a landform signature (Pike, 1988) that is more discriminating than a single feature classification, but sufficiently general to be of use in an analytical context." (Wood 1996: 125). In turn, from these terrain parameters classifications of the central cell and its neighbourhood can be made into one of the six morphometric feature classes, pit, peak, channel, ridge, pass and plane. An example how a morphometric feature classification over several scales can be portrayed is given by Fig. 16, a spatial depiction of a morphometric feature classifications is shown in Fig. 17. If need be, these classifications can be aggregated into a single classification picking the modal feature classification for each cell across all scale-specific classifications.

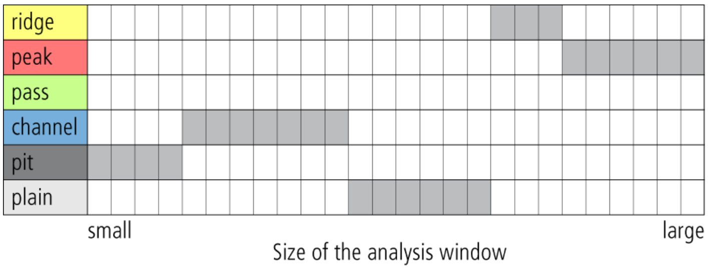


Fig. 16: Variation of the morphometric classification at a single position with scale (after Wood 1996: 124). The progression of classifications conforms to the situation sketched in Fig. 14.

When computing the aggregated modal feature classification, an entropy raster can be calculated as a measure of variability of a location's classification. When combining feature classification maps of several scales, it is possible with Wood's (1996) approach to produce a "feature membership map" and a "classification uncertainty map". Both can be combined into a single hue-intensity image.

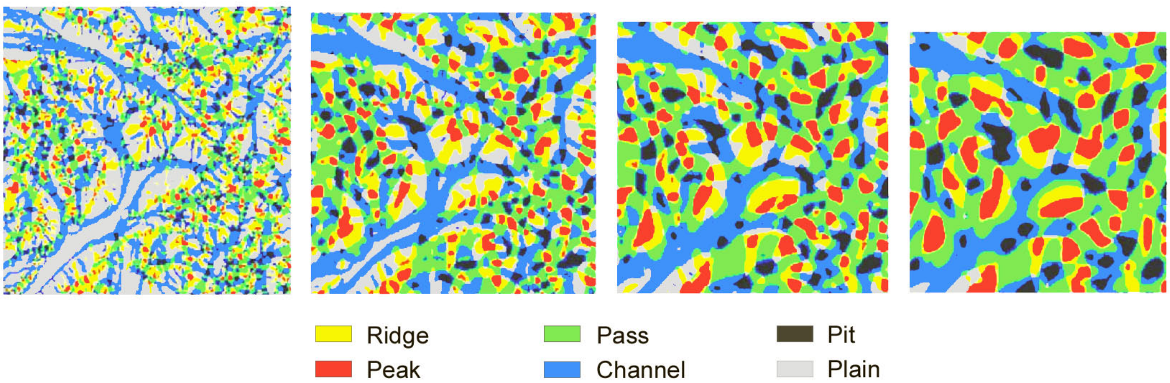


Fig. 17: Morphometric feature classification at various scales (adapted from Wood 1996: 164).

Schmidt and Hewitt (2004) applied the methodology of Wood (1996) to compute terrain parameters for their classification at appropriate scales. Schmidt and Andrew (2005: 346) computed terrain parameters at multiple scales and analysed their scaling behaviour in order to determine “appropriate landform scales”.

Similarly to Wood (1996), Sulebak and Hjelle (2003) suggested a multi-resolution spline model for DEM generalisation and scale-specific terrain parameter computation. However, their approach has not found an audience as wide as that by Wood (1996). Another set of techniques involve analyses in the frequency domain. Wavelet transforms have seen applications in many fields (Brooks et al. 2001) including digital terrain modelling (e.g. Gallant and Hutchinson 1996, Mahler 2001, Martinoni 2002, Amgaa 2003, Bjørke and Nilsen 2003).

The multi-scale analysis of landform elements was taken one step further with the seminal paper of Fisher et al. (2004). Therein the authors suggest interpreting multi-scale morphometry as fuzziness. Suppose the membership of a landform at position *x* to a morphometric feature class *A* analysed at a certain scale s_1 is denoted:

$$m_{x,A|s_1} \tag{5}$$

The membership to one class is then:

$$m_{x,A|s_1} = 1 \tag{6}$$

while the memberships to the other class(es) *B* are (let the universal set spanning the whole parameter space be Ω):

$$m_{x,B|s_1} = 0, \text{ where } B \subseteq \Omega \setminus A \tag{7}$$

(i.e. the classification is exclusive).

Analysing these at several scales enables us to integrate the individual Boolean classifications into a fuzzy measurement for the membership of the landform at *x* to a certain morphometric feature class *A* as analysed over a certain range of n scales $s_1, \ldots, s_n$:

$$\mu_{x,A} = \frac{\sum_{i=1}^{n} w_i \cdot m_{x,A|s_i}}{n \sum_{i=1}^{n} w_i} \tag{8}$$

The weighting coefficients w_i are introduced in order to enable variable weighting of the different scales of analysis. However, this possibility is not exploited in Fisher et al. (2004). Weighting coefficients for a landform elements classification were investigated in

Deng et al. (2006), however only for a single scale and for the unsupervised fuzzy c-means algorithm.

2.3.5 From landform elements to landforms

After Wood (1996: 15), geomorphometric classification can be divided into approaches that classify terrain into homogeneous regions of some sort and approaches that identify specific geomorphological features (here, Wood mentioned the extraction of valley heads by Tribe (1990) whose contributions are reviewed in Section 4.2). This distinction maps quite well onto that one between landform elements (homogeneous with regard to some terrain parameters) and landforms (larger regions of similar form character). The dichotomy can further be linked to the two contrasting (field-based vs. object-based) sets of definitions for the term *landform* (see Section 2.3.1) which yield themselves to what can be termed bottom-up approaches and top-down approaches to surface form description, respectively. Field-based bottom-up approaches define terrain parameters over an entire landscape and apply a range of techniques to identify areas within a landscape with similar attribute values (i.e. usually landform *elements*). For object-based top-down approaches the starting point is usually some notion of the landform under investigation, which in turn leads to an often custom-tailored method yielding *landform* objects rather than fields or textures of landform elements. Because of the semantically richer but also more ambitious approach, techniques aiming at landforms often focus on one landform rather than on an assemblage of multiple forms. Of course, in practice neither of the afore-mentioned distinctions is clear cut – rather there is a gradation between methodologies.

In the literature there is recently a concentration on the delineation of mountains and similar objects (e.g. Fisher et al. 2004, Chaudhry and Mackaness 2007, 2008) or, as they are also more neutrally termed, *topographic eminences* (Mark and Sinha 2006). Some of this literature shall be briefly reviewed below. Literature which is more centred on valleys and the like will be mentioned in the part of this thesis dealing with case studies about valleys and related forms (Chapters 4 to 6).

The prominence and the essence of mountains were elucidated by Derungs and Purves (2007) from an ontological viewpoint. Using a questionnaire they investigated what terms or characteristics laypeople typically associate with mountains and under what circumstances people perceive a range as composed of individual mountains. Focussing more on algorithm development, Greatbatch et al. (2007) did not explicitly derive footprints of mountains but assigned prominence values to peaks which were then in turn compared to the web-derived prominence of such features. However, implicitly this analysis is based on the assumption that the areas they compute are linked to the mountains' footprints. In their first approach, using the Landserf (s.a.) software they carried out "a peak classification exercise (…) which produced a series of peak contributing areas, altitude and relative drops for each peak" (Greatbatch et al. 2007). Secondly, they used an inverted DEM and computed inverse watersheds (watersheds draining towards peaks) as approximations to the extent of the peaks. Thirdly, Voronoi polygons were constructed around peaks. Alleviating some drawbacks of these crisp approaches Fisher et al. (2004) ask the question "Where is a mountain?" and set out an approach to the fuzzy multi-scale treatment of the six morphometric feature classes (detailed in the previous section). They hypothesise that fuzzy areas with high 'peakness' can be associated with culturally recognised peaks and similarly for passes. For testing they compare the computed fuzzy objects with toponyms from a gazetteer and find that the morphometric analysis produced more features than are recorded in the gazetteer. Fig. 18 shows an example of two peaks and their respective peakness. Although the result is a raster representation of fuzzy regions rather than individual objects, with the applied parameters the individual peaks can be clearly separated from each other.

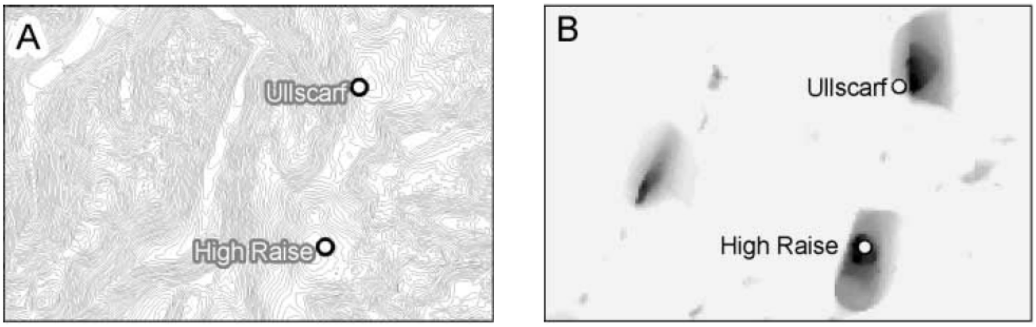


Fig. 18: Two peaks in the English Lake District on a map of contour lines (A) and the fuzzy multi-scale 'peakness' at the same location (B) (Fisher et al. 2004: 115).

Similarly, Deng and Wilson (2007) mapped mountain peaks as fuzzy multi-scale entities using a four-fold semantic import model approach employing focal downslope relief, focal mean slope, focal relative altitude and number of summit points in a neighbourhood. These characteristics are summarised per scale, each scale is in turn summarised into a multi-scale prototypicality of the peak points alone. This prototypicality is then spread out spatially by assessing the similarity with regard to the four peak criteria of all points to the most typical peak points and assigning them a similarity measure. The process can be carried out at various scales (e.g. Fig. 19 shows peakness over three scales), but depends on several user-specified parameters.

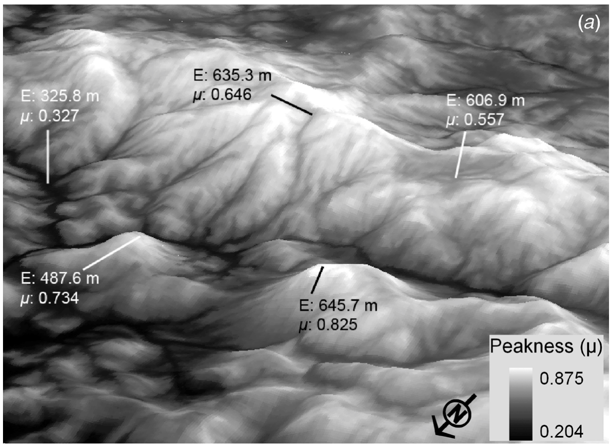


Fig. 19: Peakness (μ) summarised over three distinct spatial scales (E: elevation) (Deng and Wilson 2007: 215).

Chaudhry and Mackaness (2007, 2008) presented an approach for the identification of hills and ranges. This is vector-based and grounded both on the idea of prominence and morphological variation operationalised by the morphometric feature classification (Wood 1996). Their algorithm yields crisp, hierarchically structured ranges of hills, fuzzification of which is identified as a potential future research direction by the authors.

2.4 Research gaps

Research gaps were identified in two main areas: Firstly, the field dealing with the ontology of landforms and the domain ontology of geomorphology and, secondly, the actual task of identifying, classifying or characterising landforms from DEMs.

In the field of ontology of landforms and landform elements several research gaps can be identified. Briefly one could say that the ontology (both in the philosophical and the computer science sense after Guarino (1998); see Section 2.1.1) of landforms and landform elements is only partly analysed and not yet understood. Like Smith and Mark (2003) note, however, knowing the ontology of a domain is required for effective representations of that domain and its contents, which in turn enables scientific computing.

The terminology of the domain of landforms is very cluttered and complex; often there seem to be several terms for identical or overlapping concepts. For some landform terms it is unclear what concept should be understood from them or how that concept is to be defined and separated from other concepts. Generally, geomorphology has seen little standardisation and the abundance of qualitative and subjective terms likely stems from a long qualitative, descriptive history of the field (cf. Arrell 2002, Dehn et al. 2001: 1005, Blaszczynski 1997: 184). Refer to, for instance, Pike (1995: 223p) for a more complete description of the issue (however, we disagree with his assertion that the solution for the terminological jumble is strict adherence to exclusively quantitative terms and avoidance of any qualitative terms).

While we do have a vocabulary to characterise the nature of boundaries and thus of objects they bound (fiat or bona fide, fuzzy or hard), it is not clear in all cases what landform concept features what set of boundaries (it is generally accepted that landforms are fiat objects with often fuzzy boundaries, however, the general question remains open) and especially how they could be operationalised. Also, there are open questions regarding mereology (*part-whole* relationships) or, more generally, interrelationships of landforms and landform elements. This is tied to the distinction of landforms and landform elements as well as to the problem of the multi-scale nature of the land surface and, thus, necessarily, of descriptions of it.

While basic ontological research about the nature of landforms is rewarding, we advocate taking one step back and focussing on the mainly practical parts of ontological research; namely, first looking at what landform terminology exists at all, which landform categories may matter (most), how they are interrelated and what their characteristics are. In all of this, however, we will keep in mind the ontological findings which were portrayed in Section 2.1.

In the field of landform (element) classification there are several research gaps. Unsupervised classification approaches may be more objective than supervised approaches (disregarding for the moment the need to choose the terrain parameters which the classification will be based on and choice of the class number); however, the resulting classes need a semantic *a posteriori* interpretation (Möller et al. 2008: 420). By inspection of attribute values within landforms or landform elements, they may be assigned either a name reflecting simply these attribute values (e.g. “north-facing steep slope”), or be associated with a landform term (e.g. “shoulder slope”). Thus, in unsupervised classification approaches there seems to be no way of catering for categories which are semantically meaningful to humans. The very approach of unsupervised classification aims at minimising intra-class variance while maximising inter-class variance and is thus purely data-driven and not model-driven. Thus, probably unsupervised classification approaches are not apt for providing semantically meaningful descriptions of land surface form (that is not saying that they cannot provide very worthy descriptions for some applications like soil classification or sampling).

Supervised classification approaches are based on heuristics which are derived from semantic import models or directly from pre-existing heuristics such as expert knowledge or from the literature. Thus, in supervised classification approaches there is usually more subjectivity and arbitrariness with the beneficial trade-off of more control over the semantic content of derived landform (element) classes. However, we think that not all supervised classifications give enough attention to the *a priori* identification and characterisation of a landform (element) concept. Also, for example, Dehn et al. (2001: 1006) criticise "classical approaches of landform representation" for not explicitly applying semantic modelling in their approaches. This links back to some of the uncertainties and unknowns identified in ontological research described above. Summarising briefly, although a semantic approach to landform modelling is deemed advantageous and desirable (Dehn et al. 2001), there is a lack of semantics in both unsupervised and (though to a lesser extent) supervised approaches with the latter lending itself more easily to better inclusion of semantics in the classification process.

In hands-on work, with both unsupervised and supervised approaches, there are arbitrary choices (e.g. of terrain parameters, possibly the weighting of terrain parameters and the methodology in unsupervised classification and e.g. of terrain parameters, possibly their weighting and classification criteria and thresholds in supervised classification). Adopting a multi-scale perspective both approaches need to choose an appropriate scale level or, more recently (with more sophisticated approaches which integrate over several scales) an appropriate range of scales for analysis. Only recently has research emerged which aims at identifying such scales for landform (element) analysis (e.g. Schmidt and Andrew 2005), however, no conclusive heuristics have been suggested.

All these factors include a significant amount of subjectivity, arbitrariness, fine-tuning and adapting of sometimes many parameters in the classification process. The choices involved are not always reflected and the results are often subjected to visual interpretation and evaluation only. An identifiable research gap is thus the lessening of the dependency of landform (element) classification approaches from numerous parameters and a more objective validation of the results.

Further, research into land surface form description has (except for simpler characterisations such as the mere computation of terrain parameters) often focussed on *landform elements* rather than *landforms*. This is probably due to the easier and less subjective definition of landform elements (regions with similar values for a set of terrain parameters) and due to the direct applicability of such features within a soil-landscape modelling framework or other applications. Further, many landform element classes put forward in the literature are more geometrically than semantically defined and thus leave less room for controversy.

Of the approaches which centre themselves on *landforms* rather than landform elements, notably many focus on the delineation of mountains or more generally, *topographic eminences* (Mark and Sinha 2006). Resonating with this circumstance, Hugget (2007: 232) – a geomorphologist – stated that "valleys are so common that geomorphologists seldom defined them and, strangely, tended to overlook them as landforms". Thus, it is an attractive and interesting choice to focus on *topographic depressions* such as valleys.

2.5 Research questions

From the background described and from the research gaps sketched the following research questions were formulated for this thesis. Table 2 shows which chapters of this thesis deal with which research questions.

RQ1 **What landforms are often referred to in reference works and standards?**

RQ2 **How are these landforms defined?**
How are different landforms related to each other?
Can a taxonomy of landforms be developed?

RQ3 **How can a landform be formalised to be treatable within a GIS?**

RQ4 **Can landform concepts be exploited for practical use in, for example, a characterisation algorithm?**

RQ5 **Can the characterisation algorithm successfully extract the landform in question from a DEM?**

RQ6 In turn, to what use can an extracted landform be put, in, for example, geomorphology and in the description of landscape?

Table 2: Attribution of research questions to chapters of this thesis.

	Chapter 3	Chapter 4	Chapter 5	Chapter 6
RQ1	●			
RQ2	●			
RQ3		●	•	●
RQ4		●	•	●
RQ5		●	●	●
RQ6		•	●	●

"Toward evening he came to the mountain ridge, to the snowfield from which one again descended westwards into the plain, he sat down at the crest. Things had grown more quiet toward evening; the clouds lay still and solid in the sky, as far as the eye could see, nothing but peaks, broad downward slopes, and everything so silent, gray, twilit; a terrible solitude came over him, he was alone, all alone, he wanted to talk to himself, but he could not, he hardly dared breathe, the crunch of his foot sounded like thunder beneath him, he had to sit down; he was seized by a nameless anxiety in this emptiness, he was in a void, he sprang to his feet and raced down the slope."

from *Lenz* by Georg Büchner

3 Extracting domain knowledge about landforms

As mentioned in Section 2.1 the conceptualisation and recognition in situ of landform and landform elements has been described as the fiat parsing of the elevation field (Smith and Mark 2003: 420). This notion lies at the heart of the next section which deals with the dichotomy of smoothly varying fields or surfaces on one hand and well-defined objects on the other hand.

The aim here is to investigate the ontology of landforms. Practically, this part of the thesis is devoted to structuring the breadth of landforms into a taxonomy which can support the task of landform extraction or characterisation. When in the subsequent text a landform term refers to a category, it is set in *italic type*; if, instead, a landform term is set in roman type, it refers to an instance or to instances of the category of the same name.

After establishing the field-object dichotomy and how people in different areas perceive landform(s) differently, the second section of this chapter will describe the data sources used in the investigation of landform categories. Importantly, the construction of the taxonomy is done with the limited resolution (about 100 metres) of the SRTM DEM in mind. SRTM DEM is an almost globally available dataset and thus considered to be an attractive base dataset for developing landform characterisation approaches both within this thesis and also in future work. We think that 100 metres resolution are enough to already yield a rich set of candidate landform categories and we would argue that much of the human appreciation and conceptualisation of land surface forms occurs rather at the coarse end of the resolution spectrum, while small and micro forms such as, for example, small rills or ripple marks are of less interest in that context. Hence, landforms which are not detectable at SRTM resolution will not be included in the taxonomy. Additional reasons for exclusion of certain landforms are detailed in the third section along with some general considerations regarding landforms and their superordinate levels. Fourthly, the actual taxonomy itself is described and depicted. Lastly, a brief section leads over to the second part of the thesis comprising Chapters 4 to 6.

3.1 The field-object dichotomy

3.1.1 Geographic information scientists

In geographic information science there are two accepted paradigms for the conceptual modelling of real-world phenomena. According to Weibel and Heller (1991) topographic surfaces have most often been modelled as fields. As opposed to the second conceptual model known as object model in geographic information science, the field model assumes a property (elevation in the case of DEMs) is given at any location in space and is (roughly speaking) varying smoothly throughout space. With geomorphometry becoming popular (Evans 1972), the field conceptual model underlying the common elevation data structures became the basis of the quantitative, GIS-based treatment of geomorphology. Apart from the simplest parameters of general geomorphometry – slope gradient, slope aspect and curvatures – a variety of geomorphometric parameters can be derived or approximated from digital elevation models (Mark 1975, Weibel and Heller 1991, Moore et al. 1991; see also Section 2.2 and Appendix A). Usually, the parameters which can be represented spatially are conceptualised as fields in the same way as the underlying elevation information.

Because of the dichotomy between the field model and the object model in geographic information science there are tools that help in the transition from fields to objects (the process of extraction or delineation, perhaps with (subsequent or simultaneous) classification) and vice versa (the process of interpolation or simply conversion). However, in order to extract objects from a field-based representation, one has to know what objects one is looking for, what their properties and possibly interrelations are. Only with this a priori knowledge one can try to devise an appropriate methodology. This stance leads to the investigation of landform categories carried out in this section. However, before arriving there, it is useful to briefly look at the perception (or non-perception) of the field-object dichotomy in other areas.

3.1.2 Laypersons

We can find a perspective opposed to the field model within geographic information science, when we look at laypersons. When in their daily life people engage with the world around them, they use some kind of conceptualisation, i.e. a "system of concepts or categories that divides up the pertinent domain into objects, qualities, relations, and so forth" (Smith and Mark 2003: 414). This dissection of the world into individual objects serves as a means to avoid cognitive overload. Regarding the realm of everyday reasoning (or "folk disciplines") Smith and Mark (2003: 419) hypothesise that – opposed to science – there is no dichotomy of field conceptualisations versus object conceptualisations: "The naïve or folk disciplines appear to work exclusively – or at least overwhelmingly (…) – with object-based representations of reality". Section 2.1 has highlighted some features of human cognition which allows us to arrive at an understanding of the world as being composed of objects.

3.1.3 Social scientists

Interestingly, some of the categories that are used by laypersons and by geomorphologists to describe forms on the earth's surface are also used by other professionals. In this category are for example social and economic geographers. Depending on their scientific background, these professionals are probably aware of the field-object dichotomy.

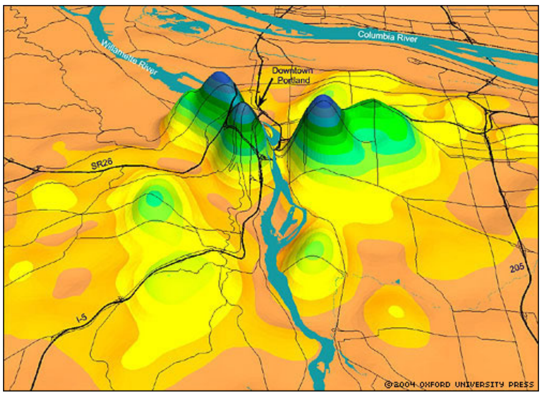


Fig. 20: A density surface of home locations of research subjects (Kwan and Lee 2004).

The works by Kwan (2000) and Kwan and Lee (2004) can serve as good examples how (geo)morphologic notions are indeed also used within a social-economic geography context. The authors use density surfaces to analyse and compare spatial activity patterns (Fig. 20). They feel comfortable and apparently find it useful to talk of "peaks", "troughs" and "saddles" of such density surfaces – without further defining these. Wood et al. (1999) investigated the use of geomorphometric measures and the morphometric feature classification on (among others) population density surfaces of London and could highlight some interesting potential applications.

3.1.4 Geomorphology professionals

When we look at professional geomorphology, an important branch of it was (is) dedicated to describing specific landforms or landform elements and landscapes in terms of surface forms. There are standard or reference works that aid professionals developing a vocabulary to deal with these tasks (e.g. Blume 1992). Some geomorphologists (be it simply through their scientific education or through their interest in the quantitative measurement of surface form) may be aware of the possibility of viewing and representing their subject in the field model view and thus of the field-object dichotomy. However, we suppose the majority of geomorphologists are very used to thinking of the world being populated by objects. Hence, much geomorphology deals with the mapping and description of landforms and landform elements and with elucidating the origins as well as the further development of these. So, similar to laypersons, for geomorphologists the formation of objects out of fields is also part of their everyday business.

This short overview demonstrates the ubiquitous usage of concepts or categories in describing land surface form. Still, the popular, ubiquitous use of the object model has only marginally led to sound investigations of the underlying concepts. This, however, is the endeavour of this part of the thesis.

3.2 Data sources

In order to elucidate landform categories we start from existing descriptions. In terms of reference works, some of the well-known, general (e.g. data exchange) standards feature sections which apply to geography or geomorphology. A selection of such standards and reference works are listed in Table 3 and are described in more detail in the subsequent sections. The hypothesis of this approach is that such standards occupy themselves with categories that are for some reason interesting to humans as well as for system development and system interoperability.

A short sub-section will present the most prominent additional pieces of literature which were used in the process of taxonomy construction. These additional sources are geomorphology or geosciences dictionaries and textbooks and where mainly employed in arbitration for differing definitions or views and in deepening of the taxonomy where the standards and reference works in Table 3 were deemed too shallow.

Table 3: Standards and reference works.

Name	Reference(s)	Abbreviation
WordNet	Miller (1995), WordNet (2009)	WNET
American National Standards Institute (ANSI) National Committee for Information Technology Standards (NCITS) 320-1998 – Spatial Data Transfer Standard (SDTS)	ANSI (1998), U.S. Geological Survey (2005)	SDTS
Ordnance Survey Hydrology Ontology	Ordnance Survey (2009)	OSHO
Digital Geographic Information Exchange Standard (DIGEST)	DGIWG (2000, 2009)	DIGEST
Alexandria Feature Type Thesaurus	ADL Project (2002a,b)	AFTT
Suggested Upper Merged Ontology (SUMO), domain ontology of Geography	Niles and Pease (2001), SUMO (2009), Nichols (2004)	SUMO-G
Oxford English Dictionary	OED (2009)	OED

3.2.1 WordNet

WordNet (version 2.1) is a lexical database of the English language held at Princeton University. Its development formally began in 1985 and drew upon various sources as input such as corpuses, thesauri, lists of synonyms and lexica (Fellbaum 1998: xv; WordNet 2009).

Word types (nouns, verbs, adjectives and adverbs) are grouped into synsets. These represent what are termed cognitive synonyms and each synset stands for a distinct concept. Different synsets are interlinked by various relations (WordNet 2009) such as hypernymy (being a class of something), hyponymy (being a member of a class), holonymy (being the whole consisting of parts, substance or members) and meronymy (being a part, the substance or the member of something). This structure makes WordNet suitable for use in computational linguistics and natural language processing. Regarding landform categories or concepts WordNet features a synset called *geological formation, formation*. Most landforms seem to reside beneath that synset.

3.2.2 Spatial Data Transfer Standard

As its name implies, the Spatial Data Transfer Standard (SDTS) was designed to ease or enable the exchange of spatial data between different systems and bodies. The beginnings of SDTS can be traced back to the formation of the National Committee for Digital Cartographic Data Standards for promoting and fostering the sharing of spatial data (FEDSIM 1996: 4). The standard was ratified by the National Institute of Standards and Technology (NIST) of the USA. Since 1994 American federal agencies (e.g. U.S. Geological Survey, U.S. Census Bureau, U.S. Army Corps of Engineers) have been obliged to adhere to SDTS in producing spatial data (FEDSIM 1997). Apart from specific profiles SDTS is made up of a three-part base specification. Part two of the base specification encompasses a standard set of “small- and medium-scale spatial features commonly used on topographic quadrangle maps and hydrographic charts” (FEDSIM 1997: 8) along with definitions and associated attributes. The entity types in this catalogue have been designed to be mutually exclusive, to bear standard names and to be without a pre-defined hierarchy or classification system (FEDSIM 1996: 25).

3.2.3 Ordnance Survey Hydrology Ontology

The British national mapping agency, Ordnance Survey, has formed a GeoSemantics team whose task is “to provide both an explicit representation of our organisation’s knowledge and a set of increasingly automated operations that allow different datasets to be combined together, by representing them in a semantically meaningful way via ontologies.” (Ordnance Survey 2009) As of September 2009 the Ordnance Survey Geosemantics team has developed domain ontologies for buildings and places, administrative geography and hydrology. Ontology modules regarding topography, mereological, network and spatial relations are still under development.

3.2.4 Digital Geographic Information Exchange Standard

The Digital Geospatial Information Working Group (DGIWG) was established in 1983 in order to develop standards for the exchange of geographical information among NATO (North Atlantic Treaty Organisation) member states. However, the current membership of DGIWG and its activities extend beyond NATO. The Digital Geographic Information Exchange Standard (DIGEST) was developed by DGIWG. It is a "comprehensive 'family of standards' capable of supporting the exchange of raster, matrix, and vector data (and associated text)" and has become a NATO Standardization Agreement. Nowadays, DIGEST-compliant datasets are produced and shared in various countries both for military and civilian applications (DGIWG 2009). The standard encompasses among others the Feature Attribute Coding Catalogue (FACC) which is a scheme for coding of features, attributes and their values. FACC features a physiography section which lists landform related terms without any particular hierarchy.

3.2.5 Alexandria Digital Library Feature Type Thesaurus

The Alexandria Digital Library (ADL) Feature Type Thesaurus (FTT) contains a hierarchical scheme of terms in the administrative, hydrographic, man-made, physiographic and regional places domains. It is intended to be used to type entries in a gazetteer and as a shared vocabulary for interoperability of gazetteers. The ADL-FTT was developed within the ADL Project at University of California at Santa Barbara. The last version from July 2002 encompasses 210 preferred and 1046 non-preferred terms (ADL Project 2002b) including relationships of hierarchy, equivalence and association. Landform-related concepts can be mainly found under *Physiographic features* and partly under *Hydrographic features*.

3.2.6 Suggested Upper Merged Ontology

The Suggested Upper Merged Ontology (SUMO) is a formal upper (or top-level, foundation) ontology, i.e. an ontology of very general concepts that are shared among all domains. It is a candidate ontology for the Standard Upper Ontology (SUO; IEEE SUO Working Group 2003). The whole SUMO consists of the SUMO itself, the Mid-Level Ontology (MILO) and several domain ontologies among which there is also one for geography (SUMO-G). The latter contains the concept *LandForm*. This category is defined as “the class of geographically and/or geologically distinct areas that occur on Earth’s surface, including mountains, hills, plains, valleys, deltas, and features of submerged land areas such as the ocean floor”.

3.2.7 Additional literature

Table 4 shows the most often used pieces of additional literature for the elucidation of landform categories.

Table 4: Additional literature.

Author(s) / editor(s)	Year	Title
Huggett	2007	Fundamentals of Geomorphology
Ahnert	1998	Introduction to Geomorphology
Rice	1988	Fundamentals of Geomorphology
Allaby and Allaby	1999	A Dictionary of Earth Sciences
Mayhew	2004	A Dictionary of Geography
Whittow	2000	The Penguin Dictionary of Physical Geography
Kearey	2001	The New Penguin Dictionary of Geology
Lapidus et al.	2003	Collins Dictionary of Geology
–	2003	McGraw-Hill Dictionary of Earth Science

3.2.8 Exclusions of terms

The reference works listed in the preceding sections were scanned for landform-related terms in the categories mentioned in sections 3.2.1 through 3.2.6. However, in order to sensibly deal with the amount of information, the scope of this ontological analysis has been confined in the following ways.

Since this thesis deals with the characterisation of land surface form, we excluded from our investigations all features that are below high water level or are closely tied to water in some way. These include *atoll*, *(sand) bar*, *beach*, *bed, bottom*, *channel*, *(coral) reef*, *drowned valley*, *foreshore*, *(fore)deep*, *glacier*, *guyot*, *ice mass*, *oceanic abyss*, *sandbank*, *seamount*, *shelf valley*, *shoal*, *spring, fountain, outflow, outpouring, natural spring*, *submarine canyon*, *swell* and *tidal basin*.

Further we excluded features of (predominantly) human or animal origin which were sometimes listed under landform-related superordinate categories, for instance, *seawall*, *bulkhead*, *non-tidal basin*, *embankment/fill*, *moat*, *cut*, *barbecue pit*, *borrow pit*, *divot*, *fire pit*, *burrow*, *gopher hole*, *rabbit burrow* and *wormhole*.

Additionally we excluded terms describing forms of coastlands or arrangements of water and land such as: *bank*, *river bank*, *bight*, *cape*, *promontory, headland, head, foreland*, *mull*, *point*, *isthmus*, *peninsula*, *archipelago*, *beach*, *lakefront*, *oceanfront*, *seacoast*, *mouth* and *shore*. Some of these probably cannot be adequately investigated using digital terrain modelling anyway.

Fourthly we excluded features that are of geological nature rather than surface forms, such as *aquifer*, *fault*, *folium*, *monocline*, *mineral vein*, *relict* and *water table*, *water level*, *groundwater level*. Also, one non-terrestrial category was excluded, namely *lunar crater* from WNET.

Further, we excluded two kinds of divides; *watershed divide* (from SUMO-G) and *continental divide* (AFTT). Both these divides are not very well recognised as landforms of their own when viewing a landscape. The watershed divide may be (re)cognised as a mountain ridge, while the continental divide, firstly, is usually too big to be viewed from a single point, and, secondly, may be not very distinct in terms of its visual salience (e.g. not much higher than 'ordinary' divides). On the same grounds we excluded the category *ridge line* (from SDTS and DIGEST) defined (by SDTS) as "the line separating drainage basins". DIGEST defines the same category as "a line representation of a ridge top". This definition alludes more to cartographic needs than to geomorphological categorisation. For the same reason we excluded *bottomline of cliff* and *topline of cliff* (from DIGEST as well).

Other features we excluded from our listing encompass features that are not contained in standard DEM representations because of their 2.5D nature (Penninga 2008: 14) (*cave* and along with this the category *cave matrix*, as well as *ledge*, *shelf*, *berm*, *(sea) arch*, *(natural) arch*). Also, as set out at the beginning of this chapter, landforms which are not deemed detectable at our working resolution of about 100 metres are also excluded from the taxonomy (e.g. *beach cusp*, *ripple mark*, *earth pillar*).

An additional remark should be made about the geographical scope of this knowledge analysis. The aim of this section is to construct a landform taxonomy which could be applied in a "Western" and, more specifically, in a mainly European setting. Thus, when a landform term was denoted to be chiefly used in the USA or in other areas of the world or when a landform term was designated to be of mainly local importance (dialect) *within* a part of Europe, it was not included into our taxonomy. Of course, these distinctions cannot be made clear-cut and we clearly acknowledge that conceptualisations of landforms and landforms elements differ amongst different languages and cultures (see Section 2.1.7) – which is why we thus constrain the scope of the subsequent analysis.

In the following section we will develop superordinate categories into which the found landforms from the different data sources can sensibly be grouped.

3.3 General considerations

To elicit the most important objects that are fiat-parsed from the earth's surface we first make a thought experiment. We assume that we look at a part of the earth's surface in such a way that we can comfortably perceive it as being plain – i.e. having no undulations or irregularities. We can imagine the whole earth surface being constituted by such a surface. On such a surface there would be no distinguished features. Of course this collides with our everyday experience: the earth's surface is not flat but has irregularities. In the simplest case a surface could have a single irregularity consisting of a single point (or rather some infinitesimal area) that is not aligned with the rest of the area constituting the surface. Unfortunately, this situation cannot be adequately sketched in a figure.

In the case of an oriented surface in 3D space the formulation of this situation is somewhat less awkward: On such a surface a singular irregularity is constituted by an infinitesimal area that has a different elevation (above whatever is the reference) from the other areas. A surface can basically have two sorts of irregularities – it can be deformed up or down in some location. Thus, we may advocate three categories: maxima, minima, neither. The very notions of *up* and *down* (and the notion of elevation used earlier) imply some axis of reference – they can only come into existence, they are *granted* by an axis of reference. In the case of the earth's surface this is the axis of gravity which is experienced by every human being.

However, *being deformed up* or *being deformed down* obviously implies more. To help disregard any unwanted geological connotations of these terms, we replace them by *elevated* and *depressed*, respectively. A part of the earth's surface can only be called *elevated* or *depressed*, if its (average? typical?) elevation can be assessed with regard to other parts of the same surface. In other words, being *elevated* or *depressed* is a relational property of a surface part – a property that can only be stated with respect to something else than the thing in hand.

In what follows we call elevated parts of the earth's surface *topographic eminences* and depressed parts *topographic depressions*. The term *eminence* is not only used for distinguished superiority or as a title of honour but also for elevations on the earth's surface (OED 2009). David Mark (personal communication, 28 June 2007) highlights an early scientific publication about the domains of the Hopi (a Native American people) language by Voegelin and Voegelin (1957) that uses the term in this way. We add the prefix *topographic* to it to make the distinction clear.

Fig. 21: A hypothetical cross-section comprising a topographic eminence and a topographic depression against the backdrop of a topographic plain.

We want to use the very obvious distinction between topographic eminences and topographic depressions as an ordering principle for our taxonomy of landforms. But if a topographic eminence is an elevated, and a topographic depression a depressed, area of land with respect to their surrounding area, we should have a third category for the area surrounding these irregularities (Fig. 21). Given this surrounding is (quite) flat and has a considerable extent we call it a *topographic plain*. This three-fold categorisation can – at a certain thematic granularity – exhaustively sub-divide the earth's surface (in fact, every oriented surface).

There may be a problem where the relational property outlined above is not unequivocal; for instance, a part of a surface can be elevated with respect to some neighbourhood and depressed with respect to some other neighbourhood (cf. Fig. 14, page 45, Section 2.3.4). There is also some circularity in the argument, since in order to define whether a surface part is elevated or depressed with respect to its surroundings, we first must get an idea of the extent of the surface part in question (see also Mark and Sinha (2006) on this point who advocate an iterative approach to this problem).

We here adopt the view that the three-fold categorisation into topographic eminences, depressions and plains is exclusive in a weak sense. This means that where there is a topographic eminence there cannot be a topographic depression or plain of (approximately) the same extent and vice versa. We further think that exclusivity can probably be more strongly interpreted for some categories of some granularity; for instance, we would advocate that there cannot be a rift valley where there is a mountain. However, there could by another kind of depression on a mountain, for example, rather typically, a cirque or a sink-hole or a crater. A prerequisite for a topographic depression on or within the spatial extent of a topographic eminence (and vice versa) may be that the two instances at hand are of considerably different spatial scale, as in the above examples.

Another kind of overlay of instances from different categories are *part of*-relations. Of course, the above situations of features on or within the spatial extent of other features can also be interpreted as part-whole-relations. However, in the above situations the superordinate categories of the features were not only incompatible (*topographic depression* versus *eminence*) but the candidate *part*-feature may be regarded as not essential to the candidate *whole*-feature, for example, a sink hole is not a feature specific to, or defining for, an eminence. That situation differs from that of *part of*-relations. We may say that a crater is a part of a volcano and that a plain is a part of a mesa. In such cases we may advocate that the crater or the plain, respectively, are essential and defining parts of the *whole*-feature (volcano and mesa, respectively) and not a rather non-typical (neither typical nor atypical) one which happens to be located within the spatial extent of the *whole*-feature.

Thus we can have features at a (necessarily) smaller spatial scale that overlay the three superordinate categories. For instance, we can have a cliff, a summit or even a plain (area) on or within the spatial extent of a topographic eminence such as a mountain. For features that can be parts of other features and are normally not considered to stand alone (and often do not fit into one of the three existing superordinate categories), we may introduce a fourth category with the obvious name *landform elements*, since the features inside that category may be parts of landforms in the three other categories. A typical example of a landform element in our taxonomy would be the *slope* category (possibly subdivided into prototypical kinds as in e.g. numerous landform element classification approaches, see Section 2.3). Slopes are destined to be landform elements in our taxonomy, since understood as an inclined planar feature they can per definition not be topographic eminences, nor topographic depressions nor (if markedly inclined) topographic plains.

Although they are not equally all-embracing we consider the WNET categories *(natural) elevation* and *(natural) depression*, being defined as “a raised or elevated geological formation” and as “a sunken or depressed geological formation”, respectively, as close to our respective superordinate categories. A similar category is found in DIGEST (*depression* as a “low area surrounded by higher ground”). DIGEST lacks a hierarchic structure, but the fact that features such as valleys or canyons are not listed, may give a hint at the implicit inclusion of these into the *depression* category. In SUMO-G there are the categories *UplandArea* as “a LandArea elevated above the surrounding terrain” (subclasses: *Butte*, *Hill*, *Mesa*, *Mountain*, *MountainRange*, *Plateau*, *WatershedDivide*) and *LowlandArea* as “a LandArea lower than the surrounding region, and usually level land” (subclasses: *Plain*, *Valley*).

3.4 Elucidation of landform categories

In the following three sections the breadth of *topographic eminences*, *topographic depressions*, *topographic plains* and of *landform elements* as introduced above will be discussed. At the beginning of the first three sections a tag cloud is displayed. Tag clouds are visual depictions of textual information. For the generation of the tag clouds we used the category names which are contained in the landform listing in Appendix C as category terms (leftmost column) as well as in the attributes “hyponym”, “included type”, “related”, “used for” and “broader term”. The tag clouds were produced with an online tool called Wordle (http://www.wordle.net) which sizes the tags according to their occurrence. Terms which consisted of several words separated by spaces or hyphens had to be made into a single term for the program to deal with them appropriately. Of course, the resulting tag clouds do not represent an objective and exact measure of importance. The size of a tag in the tag cloud is not only defined by its occurrence but at least in our perception also depends upon the tag length and possibly the letters making up the tag. However, the number of occurrences of a certain term in the landform listing as visualised in the tag cloud is certainly a qualitative measure of the relative abundance of the term and we thus think that the tag cloud can give a first-order impression regarding the term’s relative importance in the landform listing.

For understanding the following three sections best, the reader is encouraged to occasionally consult Fig. 29 (page 118) which is a graphic rendition of the full landform taxonomy. Of course, every taxonomy can easily be disagreed upon. Bill Bryson (2003: 360) puts it as follows: “Taxonomy is sometimes described as a science and sometimes as an art, but really it’s a battleground.” Nevertheless, the idea here is to lay out a potential framework of landform categories. We understand this taxonomy both as a tentative ordering framework we may apply onto the breadth of landform categorisations and as a stepping stone for a formal ontology of landforms which may one day emerge.

3.4.1 Topographic eminences

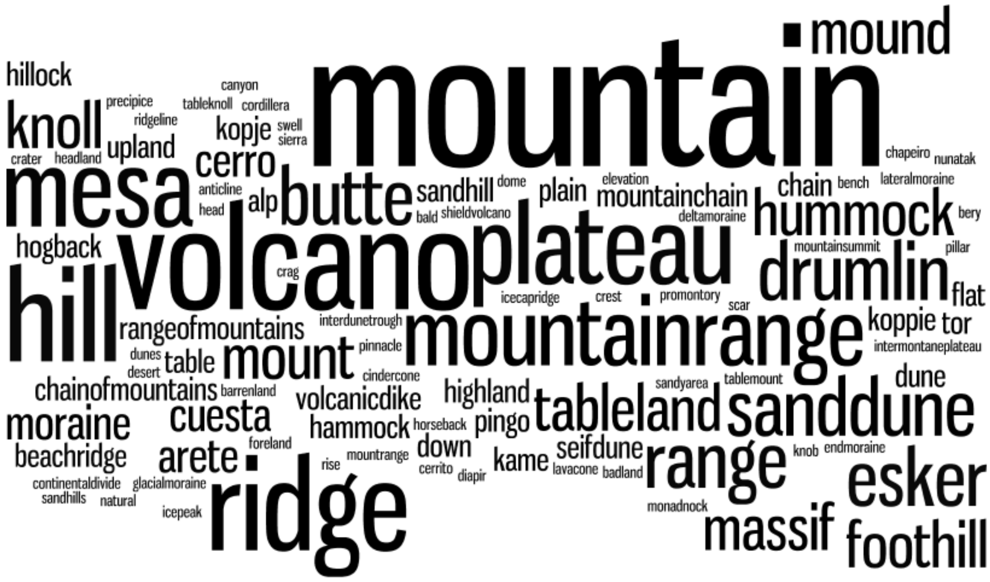


Fig. 22: Tag cloud for the *topographic eminences* listing.

Mountain and hill. Prominent categories of topography are the categories of *mountain* and *hill*. Mountains as landform features are listed by WNET, OSHO, AFTT and SUMO-G. DIGEST does not have a category *mountain* in its *Physiography-Landforms* category. However, it lists a category *hill* there which is explained as “a small, isolated elevation, smaller than a mountain”. SDTS has a superordinate category *mount* that is paraphrased as “a mountain or hill”. A category *hill* is contained in WNET, OSHO, DIGEST and SUMO-G. In AFTT *mountain* is also used for hills. So, although topographic eminences as mountains or hills usually are not depicted as objects on maps but rather hinted at (cf. Mark and Smith 2004: 75p.), such categories are included in most of our data sources.

There is a similar situation in geomorphology. Features such as mountains and hills are often not dealt with explicitly in geomorphology texts, although they are certainly very important from an everyday perspective. Maybe these categories are too basic or too general for geomorphology to deal with. Features that can be considered parts of instances of these categories or that overwhelmingly occur on instances of these categories are very often described, for example (mountain) ridges, arêtes, summits, passes, saddles, slopes, cliffs and cirques.

The conceptual uncertainty involved with the unclear/un(der)-developed dichotomy between mountains and hills does not hinder the usage of the two categories. What constitutes a mountain is not quite clear; neither where the boundary between a mountain and a hill is. Very probably, this has to do with the fact that the term *mountain* was introduced only lately into the English language (OED). There have been some attempts at a definition of mountains. However, as Owens and Slaymaker (2004: 4) note: “It is easy to get bogged down with the issue of establishing an all-encompassing definition, which may ultimately be elusive because of the huge variation of mountain types and forms and the inherent complexity of their features. There are probably greater research questions and environmental concerns in mountain areas to which geomorphologists should turn their attention.”

Let us nevertheless turn to the definitions of the categories of mountains and of hills to elucidate potential differentiations between the two. Paraphrased from the reference works, properties of mountains and hills are:

Mountain	projects well above its surroundings, large natural elevation, rising abruptly from the surrounding level, projects conspicuously above the surroundings, high and rocky, usually with steep sides and a pointed or rounded top, higher than a hill
Hill	local and well-defined elevation, naturally raised area of land, not as high as a mountain, small and isolated elevation, smaller than a mountain, raised part of the earth’s surface with sloping sides, an old mountain which because of erosion has become shorter and more rounded

Clearly, mountains are considered higher than hills and/or hills as not so high as mountains. However, it is important to state that absolute elevation was found to play a minor role in determining whether a feature is a mountain or a hill (Derungs and Purves 2007). Rather elevation is considered with respect to the surroundings: A mountain projects well or conspicuously “above its surroundings”. A second difference may be found in the horizontal extent of the features. Mountains are large elevations, while hills are local ones and/or small/smaller than a mountain. Less clear distinctions (fewer mentions) concern land cover and gradient: mountains are describes as rocky and having usually steep sides, while sloping sides are ascribed to hills. Interestingly, one source (SUMO-G) mentions the possibility of a mountain turning into a hill when it grows older and becomes shorter and more rounded. Here again mountains are considered more jagged and hills smoother. These characteristics align relatively nicely with those that Barsch and Caine (1984, cited in Owens and Slaymaker 2004: 4) found for mountains: elevation; steep, even precipitous gradients; rocky terrain; the presence of snow and ice; diagnostic vegetative-climatic zones; high potential energy for sediment movement; evidence of Quaternary glaciation; and tectonic activity and instability.

WNET lists as hyponyms of mountains (or mounts) *alp* and *ben*; the first being described as "any high mountain". OED adds to this that *alp* is used especially for high, snow-capped mountains. More interesting, however, is *ben* which is defined as "a mountain or tall hill". This term seems to allude to the not so clear distinction between the two. According to OED *ben* denotes "mountain-peak" and the term is "used with the names of Scottish mountains; e.g. Ben Nevis, Ben Lomond". *Ben* is the English rendering of Irish and Scottish Gaelic terms for mountain, crag, peak, crest, pinnacle or summit (*benn*, *binn*, *beann*, *beinn*) (McKillop 1998) and thus probably predominantly used in Great Britain and Ireland.

What can we say about compositions or juxtapositions of the features introduced above? Some definitions of mountains and hills emphasise the singularity of these features: mountains rise "abruptly from the surrounding level", hills are described as "small and isolated" elevations. This goes nicely with the assertion by Smith and Mark (2001: 598) on primary theory categories: "(…) for most such categories, some members are better examples of the class than others and they are cognized as such. That is to say, humans can distinguish easily between the prototypical instances at the core of common-sense categories and the fringe instances in the penumbra." There are certainly mountains that are surrounded by a level expanse of land of a certain extent and there are also isolated hills. However, situations are easily conceivable (in fact, we think: more probable) where mountains and hills occur in groups rather than being located alone on a plain. In close juxtapositions, however, the delineation of individual mountains may be much harder to do, i.e. the conception of a mountain or hill isolated in a level surrounding maybe is, for the sake of the definition, purposefully made to add to the prototypicality of the feature – maybe even in contradiction with reality where such topographic eminences often occur in groups.

In WNET there is a special mixed juxtaposition mentioned. A foothill is defined there as "a relatively low hill on the lower slope of a mountain". This category is not picked up by any of the other reference works. In WNET *foothill* is a hyponym of *hill*. It can be argued indeed that foothills do not differ very much from common hills except for their immediate neighbourhood. Foothills are "on the lower slope" of a larger topographic eminence (mountain) rather than being located on a plain or next to other hills of more or less equal size. We thus consider *foothill* a kind of role a hill can adopt depending upon its neighbourhood rather than a category of its own.

The next section deals with juxtapositions of mountains.

Mountain range. The data sources contain categories to hold groups of mountains and hills, as well. WNET has a synset *range, mountain range, range of mountains, chain, mountain chain, chain of mountains* describing these as "a series of hills or mountains", SDTS has *mount_range* as "a series of connected and aligned mountains or mountain ridges", AFTT *mountain ranges* and SUMO-G *MountainRange*. AFTT's mountain ranges are defined twofold: (a) as "chains of hills or mountains" and (b) as "somewhat linear, complex mountainous or hilly areas". SUMO-G's mountain range is "a row or chain of connected mountains". OSHO and DIGEST hold no corresponding categories. DIGEST, however, describes a *mountain pass* as "a natural route through a low place in a mountain range". Summarising, it can be stated that a mountain range is a grouping of mountains. Several definitions mention, that the mountains are "connected" – what that exactly means remains unclear. All definitions hold hints to the linearity of the phenomenon. WNET and SDTS calls a mount(ain) range a "series" of (SDTS:) "aligned" mountains. Other words used are "chains" (in the case of WNET as member of the synset) and "rows". This linearity is probably a predominant characteristic since many groups of mountains are a result of uplift of the earth's crust where two tectonic plates collide. This process itself tends to be a linear phenomenon.

Regarding composition, however, one must not forget that the term *mountain range* not only encompasses mountains but probably quite a large group of intervening valleys too, which cut and structure the mountain chain. Without these valleys there would not be *several* mountains. Clearly, however, the concept *mountain range* (also judged from its name) relates to the topographic eminences contained therein rather than the topographic depressions.

Massif. *Massif(s)* is defined as "a block of the earth's crust bounded by faults and shifted to form peaks of a mountain range" (WNET) and as "massive topographic and structural features, commonly formed of rocks more rigid than those of their surroundings" (AFTT). In the latter definition the link between massif and its being massive is made explicit. OED as well emphasises the massiveness of the material: there, massifs are "usually composed of older more resistant rock than its surroundings". In WNET massifs are identified as parts of the synset *mountain range*. Massifs are closely related to mountain ranges. However, they may include as an additional characteristic the massiveness of their building material. The massiveness can also be understood in another way; OED states that the term massif is used especially for "a prominent mountain mass or compact group of mountains". We deem massif as a specialist category with close relations to geology (structure, fault systems, material properties) rather than geomorphology alone and thus decide not to explicitly contain it in the landform taxonomy.

Volcano. To a lesser degree geology-dependent is the category of volcanoes. Of course, all volcanic features on the earth's crust are bound to igneous rocks, but besides this fact, they have other very prominent defining characteristics (that themselves are causally linked to the occurrence of igneous material).

In WNET the synset *volcano* is a hyponym of the synset *mountain, mount*. Thus, a volcano is described as "a mountain formed by volcanic material". In DIGEST a volcano is defined as a "mountain or hill, often conical, formed around a vent in the earth's crust (…)". Yet another approach to the categories *volcano* is taken by SUMO-G. There the *volcano* category is defined as "a volcano in the broadest sense, i.e., a region containing a vent through which magmous and/or pyroclastic materials are passed from the interior of the earth to its surface (atmospheric or underwater)". Note the extent of a volcano is thus undefined. Then there are two sub-classes to *volcano* in SUMO-G: *VolcanicMountain* (subcategory of *mountain* and *volcano*; defined as "cone-shaped mountain formed out of rock or ash thrown up from inside the earth, frequently with an opening or a depression at the top") and *VolcanicCone* (subcategory of *hill* and *volcano*; defined as "hill of lava or pyroclastics surrounding a volcanic vent. Not as high as a VolcanicMountain").

We take the view that volcanoes are very distinct features not only because of their composition of igneous rocks and the related processes but also because of morphologic properties. Volcanoes are situated around vents in the earth's crust as virtually all definitions from our reference works suggest. The WNET definition does not explicitly mention a vent but there the *volcano* synset has (among others) the meronym *(volcanic) crater*; which is an appropriate landform category for the region around the vent. There is an inconsistency with the SUMO-G definition of *VolcanicMountain* which states that volcanoes have "frequently an opening or a depression at the top". WNET itself shows a contradiction between the meronyms *(volcanic) crater* and *mountain peak* (inherited from *mountain, mount*; defined as "the summit of a mountain") for volcanoes. We think a volcano having a crater at its top is usually not characterised as having a mountain peak. In fact, volcanoes can have several elevation maxima along the rim of their (main) crater, but, clearly, the dominant characteristic feature is the crater at the top.

So to summarise, a volcano is a topographic eminence built from igneous rocks that are or were thrown out of a vent. Volcanoes usually have volcanic craters at their top and sometimes on their sides. Besides these, another more or less distinctive characteristic of volcanoes is their often conical shape as mentioned in the definitions by DIGEST and SUMO-G and the quite perfectly circular footprint.

In DIGEST there is the volcano-related category *Volcanic dike* defined as “a steep ridge of igneous rock”. We abstain from elucidating this category here, since it seems to be rather specialised and is listed in DIGEST only with no close resemblance to any category in any other reference work.

Hill-like features. A wealth of hill-like features are described in the reference works. However, not many are explicitly listed as categories. Several are contained as included types in *mount* of SDTS or in other broader terms (e.g. in AFTT). WNET has a synset *knoll, mound, hillock, hummock, hammock* meaning “a small natural hill” and *tor*, “a high rocky hill” as (among others) hyponyms of the synset *hill*. The first synset has among its hyponyms *kopje, koppie*. This feature is defined as “a small hill rising up from the African veld”. The veld (or veldt) is the “elevated open grassland in southern Africa” (WNET) or “the unenclosed country or open pasture-land” in South Africa (OED). This characterisation hints at a very localised usage of the term *veld* and in turn *kopje, koppie*, which are therefore deemed not relevant in the context of this landform taxonomy. For the remaining of the above mentioned features and for hill-like features from the types included in the SDTS category *mount* (“a mountain or hill”) we looked up definitions in OED and where possible in geomorphology-related literature (Table 5).

Alone the fact that many of the hill-like features in Table 5 do not have a definition in the geomorpholy literature indicates that many of these are not very formalised and therefore not necessarily scientific concepts or categories.

Table 5: Hill-like features in geomorphology literature and in OED.

Category	Source	Definition from geomorphology literature *Definition from OED (landform-related)*
knoll	WNET SDTS AFTT	– *1. the summit or rounded top of a mountain or hill (obsolete except dialect)* *2. a small hill or eminence of more or less rounded form; a hillock, a mound*
mound	WNET SDTS AFTT	– *3. a. an artificially constructed elevation or heap of earth, stones, debris, etc.; a pile of earth heaped up on a grave; a tumulus* *c. a small naturally occurring elevation resembling a heap or pile of earth; a hillock. Also in extended use.*
hillock	WNET SDTS	– *1. a little hill* *2. a small mound or heap of earth, stones, or the like* *3. a hump, bump, protuberance, or prominence on any surface (obsolete)*
hummock	WNET SDTS DIGEST	– *1. a protuberance or boss of earth, rock, etc., usually conical or dome-shaped, rising above the general level of a surface; a low hillock or knoll* *a. originally a name given by mariners to a hillock, or small eminence of land resembling the figure of a cone, and appearing on the sea-coast of any country* *b. (in Colonial and U.S. use) a piece of more or less elevated ground, esp. in a swamp or marsh; spec. in the southern U.S., an elevation rising above a plain or swamp and often densely covered with hardwood trees; a clump of such trees on a knoll ("hammock" in Florida and adjacent states)* *c. a sand hill on the sea shore* *d. Geology an elevated or detached boss of rock* *f. generally a boss-like protuberance rising irregularly from any surface; a knoll, hillock, or small piece rising abruptly above the general level, and causing inequality of the surface*
tor	WNET	"Tors develop in a similar way to bornhardts. They are usually formed of plutonic rocks such as granite in which there are perpendicular tectonic and horizontal pressure release joints. The tors were originally resistant remnants preserved in the regolith. When this was washed away, the free-standing tors remained (Linton, 1955)." (Ahnert 1998: 223) *1. a. a high rock; a pile of rocks, generally on the top of a hill; a rocky peak; a hill. (…)* *b. Locally in Scotland, applied to an artificial mound; a burial mound*
monad- nock	SDTS	(This category will be dealt with in one of the following sections)
bald	SDTS	– *1. a mountain summit or region naturally bare of forest, esp. in the southern Appalachians. U.S.*
bery	SDTS	– *(berry) a mound, hillock, or barrow (obsolete except dialect)* *(berry with spelling variant bery) 1. a (rabbit's) burrow / 2. transferred sense an excavation; a mine in besieging*
dome	SDTS	"An uplifted section of rocks, such as the Harlech Dome of North Wales. The highest part is at the centre, from which the rocks dip in all directions. Volcanic domes may be formed from slow-moving, viscous lava. These domes may be rounded as the result of pressure from lava below. A plug dome is a small, irregular dome within a crater. Plug domes may have spiny extrusions projecting from them." (Mayhew 2004) *4. b. the convex rounded summit of a mountain, a wave, etc. In U.S., frequently entering into the names of rounded mountain peaks* *c. Geology any of various kinds of geological structure resembling a dome in shape*

Table 5 (continued).

Category	Source	Defintion from geomorphology literature *Definition from OED (landform-related)*
cuesta	SDTS AFTT	(This category will be dealt with in one of the following sections)
kame	SDTS	"The Gaelic word kame, meaning a steep-sided hill made of unconsolidated material, is used as a term to describe isolated debris deposits under stagnant glacier ice that, after melting, remain in the landscape as small hills." (Ahnert 1998: 276)
		"An isolated hill or mound of stratified sands and gravels which have been deposited by glacial meltwater. Some kame deposits show slumping on a side which previously had been held in position by a wall of ice. Many kames seem to be old deltas of subglacial streams." (Mayhew 2004)
		"Steep-sided mound composed of bedded sand and gravel which often shows signs of marginal slumping. It is a land-form of glacial deposition, associated with stagnant ice whose removal by melting causes the collapse" (Allaby and Allaby 1999).
		Northern dialect. and Scottish form of Comb in various senses, esp. that of a steep and sharp hill ridge; hence in Geology one of the elongated mounds of post glacial gravel, found at the lower end of the great valleys in Scotland and elsewhere throughout the world; an esker or osar.
knob	SDTS	"At the end of a glacier with a large number of crevasses, blocks of dead ice become separated even with small oscillations of the glacier's terminal, so that the accumulation of the end moraine and the formation of kettles is more or less simultaneous and in proximity. The resulting knob and kettle landscape is typical of young end moraine." (Ahnert 1998: 274)
		(knob and kettle) "The landscape sometimes found on a recent terminal moraine complex and consisting of a hummocky mound (the 'knob') alternating with a depression (the 'kettle'). The 'kettle' results from the melting of a block of ice enclosed in the drift." (Allaby 2006)
		2. a prominent isolated rounded mound or hill; a knoll; a hill in general; esp. in U.S.

Considering the OED definitions of *knoll* (2.), *mound* (3.c.), *hillock* (1.) and *hummock* (1.) we agree with the interpretation of WNET that these terms should be merged together. SDTS and AFTT do not provide definitions for the above-mentioned terms. *Hummock* is defined by DIGEST as "an area of higher elevation within a swamp, bog, or marsh". This corresponds to the OED definition 1.b. and to the alternative spelling *hammock* and represents the northern American use of the term. Interestingly, *hammock* is contained in the WNET synset as well, although the definition there does not constrain the occurrence of such features to swamps, bogs or marshes. So summarising, we hold to the definition of WNET for *knoll*, *mound*, *hillock* and *hummock*, which is "a small natural hill".

Considering the OED definition (mountain summit, especially in the southern Appalachians, USA), we deem *bald* as superfluous in our category system. This category can be aptly named *summit* or *peak*. Besides, there is, according to OED, the connotation of a region naturally bare of forest. Consequently, in SDTS *bald* is an included type in both *mount* and *clearing*. However, the second connotation does not relate to landforms but to landcover.

SDTS features the term *knob* as included type in *mount*. OED suggests a meaning quite similar to *knoll* and its synonyms. *Knob* is not common in geomorphology literature except for the term "knob and kettle landscape" that denotes a terminal moraine complex modified by dead ice. In that usage *knob* stands for a "hummocky mound" (Allaby 2006). We thus decide to also use *knob* synonymously with *knoll* and its synonyms.

Another term introduced by SDTS alone is *bery*. It is an included type in both *mount* and *iceberg*. Except for the OED definition (for "berry", actually) we could not find another landform-related meaning of the term. According to OED *berry* is a variant of *barrow* and it is defined as "mound, hillock, or barrow". Since OED marks the term *berry* as obsolete except for dialect we exclude it (and *bery*) from our landform taxonomy.

Tor is only found in WNET. Ahnert (1998) gives it a very specific and specialist meaning. OED on one hand describes it as a part of a hill (a pile of rocks on top of a hill, a rocky peak) and thus rather as a landform element and on the other hand describes its use as confined to Scotland for human-made features. We could not find other references to the term, which thus does not seem to be very popular. We thus exclude it from our landform taxonomy.

The term *kame* is introduced in SDTS as an included type in *mount* and *ridge*. According to OED *kame* stems (via northern dialect and Scottish) from *comb* especially in the meaning of "a steep and sharp hill ridge". According to OED, it is hence used in geology for "elongated mounds of post glacial gravel, found at the lower end of the great valleys in Scotland and elsewhere throughout the world". OED also equates it with "esker or osar" (these are usually meandering gravel deposits from subglacial meltwater streams). According to Ahnert (1998: 276) *kame* originally meant "a steep-sided hill made of unconsolidated material" and is nowadays used for "isolated debris deposits under stagnant glacier ice that, after melting, remain in the landscape as small hills". Mayhew (2004) defines *kame* as "an isolated hill or mound" again of glacial deposits (sand and gravel). Allaby and Allaby (1999) characterise it as "steep-sided mound" of the same composition. We put *kame* as a subcategory to *knoll* and its synonyms.

The term *dome* introduced as an included type of *mount* in SDTS seems to be primarily a geological term. It is defined as "the convex summit of a mountain" or as "any of various kinds of geological structure resembling a dome in shape" (OED) or as "an uplifted section of rocks" with "the highest part (…) at the centre, from which the rocks dip in all directions" (Mayhew 2004). Familiar types of domes are granite, lava and salt domes. We think that the term *dome* does not serve well as an autonomous category, since it seems to be able to represent “any of various kinds of geological structure” (as OED puts it) from dome-shaped mountains to dome-shaped lava hills of much smaller scale. We think *dome* should be used as an additional descriptive form rather than as a landform term on its own. Half Dome in Yosemite Park (USA), for example, can be described as a mountain with the shape of a (half) dome. The term *diapir* of WNET (“a domed rock formation where a core of rock has moved upward and pierced through the more brittle overlying strata”) is closely related to domes. Ahnert (1998: 57) even equates diapirs with salt domes. Allaby and Allaby (1999) do not confine the term to salt but also include granite as a material. For these reasons the term is not included in our taxonomy.

Pingos and palsas are other features that we deem kinds of hills, although they are special in some ways. *Pingo* features in DIGEST only, whereas *palsa* is contained nowhere in the references but has been introduced subsequently by us. DIGEST defines *pingo* as “a cone or dome shaped mound or hill of peat or soil, usually with a core of ice. It is found in tundra regions and is produced by the pressure of water or ice accumulating underground and pushing upward.” According to Allaby and Allaby (1999) a pingo is an “ice-cored, dome-shaped hill, oval in plan, standing 2–50 m high, and 30–600 m in diameter (…)”. Rice (1988: 288) gives heights of 2–50 m as well, diameters of 10 to over 200 m and highlights sides that are “almost always steep and often exceed 20° in angle”. Whittow (2000: 397) gives heights of up to 60–70 m, “but the smaller ones are difficult to distinguish from palsas”.

A palsa in turn is defined by Allaby and Allaby (1999) as a “mound or ridge, largely made from peat, containing a perennial ice lens (…). Widths are in the range 10–30 m, lengths 15–150 m, and heights 1–7 m. (…).” According to Ahnert (1998: 109) the growing of an ice core is a prerequisite for a pingo to come into existence. They develop under fully periglacial conditions, whereas palsas are located “mainly on the margins of periglacial areas where permafrost is discontinuous” (ibid., cf. also Rice 1988: 281). Palsas “usually contain an ice lens but it is developed in peat and contains large amounts of organic material” (ibid.). Whittow (2000: 378) states that a palsa “differs from a pingo by the characteristic presence of peat, which is comparatively rare in pingos, that also tend to have cores of clear ice rather than the separate ice lenses of the palsa”. Summarising, it seems quite difficult to distinguish pingos from palsas based on form alone (pingos are higher, usually). Both categories fit well as subcategories to *hill*.

Monadnock, inselberg. Monadnocks are features named after Mount Monadnock (USA) (Fig. 23). A monadnock is defined as "an isolated mountain or hill of temperate regions, rising above a lowland that has been levelled almost to the theoretical limit (base level) by fluvial erosion. Such a lowland is called a peneplain (…)." (Lapidus et al. 2003). Whittow (2000) defines it as "an isolated hill or type of residual due to denudation which has left it rising conspicuously above a gentle rolling plain (peneplain)".

Fig. 23: Mount Monadnock in New Hampshire, USA (The Nature Conservancy 2004).

Lapidus et al. (2003) refer to inselbergs and unakas in the context of monadnocks. They define a unaka as basically the same as a monadnock but "greater in height and in size" and "occasionally showing in its summits or surface the remnants of an even older peneplain". Whittow in contrast explains *unaka* to be "an alternative name for a monadnock, but one which has not been universally adopted. It refers to a residual of very large size rising from a peneplain." We therefore decided to drop the (seemingly qualitative) distinction between monadnocks and unaka (both terms are not featured in any of the reference works) and use *monadnock* as encompassing term.

Inselbergs may seem similar to monadnocks. An inselberg is characterised as "a prominent steep-sided hill of solid rock, rising abruptly from a plain of low relief" (Whittow 2000) that "may have a pediment at its base" (Allaby 2006) and as "isolated residual uplands standing above the general level of the surrounding plains (…); they may be ridges, domes or hills". They are found in tropical regions, particularly in the savannah. Both Lapidus et al. (2003) and Whittow (2000) highlight the distinctions between inselberg and monadnock: "(…) even though there may occasionally be great morphological similarity between the two, [inselbergs] are not the tropical equivalent of monadnocks, which are features of temperate zones. Typical inselbergs rise more abruptly from the plains than do typical monadnocks." (Lapidus et al. 2003). Whittow (2000) draws the distinctions using process: "(…) [the inselberg] is thought to be derived by the process of parallel retreat of slopes in which pediments encroach into residual uplands during the process of pediplanation. (…) The inselberg (…) may occur as an isolated hill or residual group of hills." There are other authors that explain inselbergs as remnants of deeply weathered rock (Lapidus et al. 2003, Mayhew 2004).

Plateau/tableland, mesa, butte. *Plateau* is contained in WNET, SDTS, AFTT and SUMO-G. WNET puts *plateau* and *tableland* in one synset. According to these sources a plateau is a relatively flat/level upland area "of great extent and elevation" (AFTT) "with one steep face" (SUMO-G). According to AFTT plateaus are "considerably above the adjacent country or above sea level; commonly limited on at least one side by an abrupt descent, (…) are often dissected by deep valleys and surmounted by high hills or mountains, and have a large part of their total surface at or near the summit level". Additionally, according to Ahnert (1998: 33) plateaus have a "more or less horizontal" surface. He distinguishes plateaus from tablelands, however: According to him the latter term includes plateaus but is also used to refer to large areas of sedimentary rocks that are not elevated above their surroundings. Thus, for simplification we drop the term *tableland* from the WNET synset and use *plateau* only. WNET features the synsets *mesa, table* and *terrace, bench* as hyponyms of *plateau*. We will elucidate *mesa* shortly. However, we do not agree that *terrace, bench* should be a kind of a plateau, since WNET defines it as "a level shelf of land interrupting a declivity (with steep slopes above and below)". In our view the described intermediate position regarding elevation conflicts with the essence of the definition for *plateau*.

A mesa is characterised as having a flat top and steep edges or rock walls (WNET, SUMO-G). AFTT defines mesas as "very broad (…) usually isolated hills or mountains of moderate heights" with a steep slope or cliff on at least one side. AFTT uses the term *mesa* for buttes (another term featured in WNET and SUMO-G), as well. Generally, the close resemblance (and qualitative nature of the transition) between mesas and buttes is acknowledged (e.g. Whittow 2000, Lapidus et al. 2003, Mayhew 2004, Allaby 2006). Lapidus et al. (2003) specify the height of mesas to be 30 to 600 metres and their length from a few hundred metres to several kilometres. Buttes are smaller in extent than mesas. Allaby and Allaby (1999) state that the diameter of the cap rock of a butte is less than the height of the landform above its surroundings. They also describe a plateau as “a land-form similar to a mesa but larger”. Because of its characteristic shape that differs from core instances of the categories *hill* and *mountain* we decide to put plateaus in a category of their own. Because of the obviously gradual transition (primarily in horizontal extent) from plateau to mesa and from mesa to butte, we include the latter terms as subcategories of *plateau*.

Ridge, cuesta. WNET, SDTS, AFTT have a category *ridge*. In WNET there are several different synsets containing *ridge*. First, *ridge, ridgeline* defined as “a long narrow range of hills”, then *ridge* as “a long narrow natural elevation or striation” and as “a long narrow natural elevation on the floor of the ocean”. SDTS has *ridge* as “a long and narrow upland with steep sides” and AFTT characterises ridges as “elevations with a narrow elongated crest which can be part of a hill or mountain”. Indeed, we find the latter is important; ridges can be stand-alone features in a landscape or they can be not so much perceived as a feature on their own but rather as a part of another feature. We think this distinction is important because it may well influence the perceived extent of an instance of the category of ridges. For the stand-alone feature we adapt the definition by WNET for the first synset *ridge*: “a long and narrow topographic eminence”. There are several candidates for subcategories to this category of stand-alone ridges. For a discussion about certain types of moraines, eskers, and certain types of dunes refer to the respective sections.

SDTS features cuestas as included type of *mount* and *ridge*. AFTT uses *ridge* for (among others) *cuesta* and *hogback*. According to OED *cuesta* was originally used locally in the USA. However, it was adopted in physical geography in the sense of “a hill or ridge with one face steep and the opposite side gently sloping”. The term is Spanish and means *declivity*. Whittow (2000), Mayhew (2004) and Allaby and Allaby (1999) define *cuesta* more or less unanimously as an asymmetrical landform (Whittow and Mayhew: “ridge”) with a dip slope and a scarp slope. It is produced by differential erosion in gently dipping strata. The scarp slope is shorter and generally steeper than the dip slope. There is a close connection to *escarpment* or *scarp*. Whittow (2000) has three meanings for *escarpment*: firstly, “the steep slope terminating a plateau or any level upland surface”, secondly, “the steep face which terminates the stratified rocks of a cuesta” and thirdly, the term is sometimes used synonymously with *cuesta* (cf. also Mayhew 2004), but this use is discouraged.

Thus, while *cuesta* denotes a kind of ridge, formed by differential erosion of dipping strata, we adopt the view that *scarp* and *escarpment* refer to the steeper slope of a cuesta –

and agree with Whittow (2000) that these terms should not be used to denote a cuesta. Despite being placed in different categories in our ontology, plateaus (and mesas and buttes) and cuestas are somewhat similar. Allaby and Allaby (1999) describe the cuesta as "intermediate between the flat-topped mesa and butte and the more symmetric ridge form of the hog's back". Despite the close relation of plateaus to their inclined relatives we decided not to put them into the same category, for form reasons. While a salient part of the plateau (and mesas and buttes) is the level plain on top, there is no such counterpart in cuestas. There, because of the noticeable inclination of the strata, the meeting point of the two side slopes, the crest or ridge *sensu stricto*, is in the highest position and also the focus of the term.

Drumlin, esker. Drumlins are interesting features with differing definitions across reference works. According to AFTT these are "low, smoothly rounded, elongate oval hills, mounds or ridges of compact glacial till built under the margin of the ice and shaped by its flow, or carved out of an older moraine by readvancing ice". The broader term is *ridges*. SDTS also has drumlins as included types in the feature types *ridge* and *mount*. WNET portrays *drumlin* as "a mound of glacial drift" and emphasises its substance aspect by putting it under the hypernyms *drift → substance, matter → physical entity* (not under *(geological) formation → physical object → physical entity* as are most other landform-related terms). Both DIGEST and SUMO-G do not feature a category *drumlin*. AFTT highlights the semantic similarity of drumlins and hills. Drumlins are (by nature of their formation) very rounded and also rather small features. We think regarding size there is a semantic similarity between *drumlin* and *knoll* and its synonyms (although the former tends to be linear) and we put it there as a subcategory.

Eskers are another feature of (peri)glacial areas. WNET and DIGEST contain an *esker* category. WNET defines an esker as "a long winding ridge of post glacial gravel and other sediment; deposited by meltwater from glaciers or ice sheets". *Esker* in WNET is a hyponym of *ridge*. DIGEST also describes it as "a long, narrow ridge of sand and gravel deposited by a glacial stream". We therefore include *esker* as a subcategory of *ridge*.

Moraine. SDTS, DIGEST and AFTT feature a category dedicated to moraines. All three definitions are very similar: "an accumulation of boulders, stones, or other debris carried and deposited by a glacier" (SDTS), "an accumulation of soil and stone debris deposited by a glacier" (DIGEST) and "accumulations of earth and stones carried and deposited by a glacier" (AFTT). Other than drumlins (where AFTT has a definition with some shape information), in the descriptions of moraines there is no hint at any specific shape characteristics. Rather, moraines are described in terms of their material and their coming into existence (glaciers as agents). This is a situation similar to that of the term *dune* (see next section). In order to being able to subdivide the *moraine* category based on morphology it was enriched by referring to additional literature. Similarly to the reference works cited above, Mayhew (2004), Whittow (2000), Lapidus et al. (2003) and Kearey (2001) define *moraine* primarily in terms of material and genesis (glacial deposits). Ahnert (1998: 272) distinguishes three usages of *moraine*: debris within or on the glacier, debris deposited by the glacier and the landforms made up of these deposits. Ahnert (1998: 273f.) lists as moraine landforms: lateral moraines, end or terminal moraines, ablation moraines, push moraines, retreat moraines and ground moraines.

Lateral moraines are deposited as debris ridges at the side of a glacier or ice-sheet. They are "largely derived from rock fall" (Allaby and Allaby 1999) onto the glacier side. Young lateral moraines have a sharp ridge form with an often steeper inner slope and a less steep outer slope. However, this difference is less remarkable in older lateral moraines (Ahnert 1998: 273f.). The height of a lateral moraine is dependent on the rate of material supply onto the glacier and the rate of movement of the glacier's sides (ibid.). "As a valley glacier downwastes, a series of lateral moraines may be deposited at lower and lower levels down the valley sides." (Whittow 2000).

End or terminal moraines are located at the end (snout) of the glacier. "They are ridges of till, not usually higher than 60 m", often with crescent-shaped extent in plan (Mayhew 2004) Allaby and Allaby (1999) indicate the height range as from 1 to 100 metres. However, Ahnert (1998: 274) notes that terminal moraines rarely have a single crest. According to Whittow (2000) again the inner slope is usually steeper than the outer – for the same reasons (ice contact) as for lateral moraines. The supply of debris on the glacier tongue and the length of stationarity control the volume of terminal moraines (Ahnert 1998: 274). Even in times of stationarity the position of the glacier tongue may move some tens of metres. This movement is sufficient to widen an existing terminal moraine and to render its shape irregular (ibid.).

Ablation moraines are described by Ahnert (1998) and Mayhew (2004) and are common on retreating glaciers (Mayhew 2004). They can overlay the ground moraine and are difficult to distinguish from terminal moraines. Sometimes ablation moraines contain dead ice which, when it melts, can form a kettle hole in the moraine.

Push moraines are moraines that are pushed up by the snout of an advancing glacier or ice-sheet when it advances over pre-existing glacial drift (Allaby and Allaby 1999, Whittow 2000). Whittow (2000) mentions push moraines that exhibit thrust-faults – a hint that the material was frozen when it was pushed. Ahnert (1998) mentions as an example a push moraine of 164 metres height in Germany.

Recessional or *retreat moraine* refers to a series of end moraines reflecting several stationary phases during glacier retreat (Ahnert 1998). Lapidus et al. (2003) use the term for individual "secondary end moraines". We deem the term not necessary for our needs, since it indeed seems to equate very much to *ablation moraine*.

Finally, Ahnert (1998) highlights *ground moraine* as the depositional forms "in the area of the glacier's retreat". The material does not have to be transported at the base of the glacier, however. Mayhew (2004) describes *ground moraine* "as a blanket covering the ground" also known as "till sheet". *Ground moraine* may also denote "an irregularly undulating surface of till, glacial drift, or boulder clay" (Allaby and Allaby 1999). Ahnert (1998) describes it as forming "a more or less irregular pattern of hillocks and hollows". Especially undulating ground moraines are termed "hummocky moraine" by Allaby and Allaby (1999). "Fluted moraine" is another special type of ground moraine that exhibits long ridges and grooves in the direction of ice flow (Allaby and Allaby 1999). We think *ground moraine* and its subcategories are not relevant in our context since they are very unlikely to be detectable in coarse resolution DEMs.

Medial moraines are not described by Ahnert (1998) but are covered by various other authors. They are produced where two lateral moraines join at a confluence of two glaciers (Lapidus et la. 2003). A medial moraine "is deposited as a ridge running approximately parallel to the direction of ice movement" (ibid.) and "varies in width from a narrow ridge to a broader spread of morainic material" (Whittow 2000).

We noted above that we do not include *ground moraine* and its subcategories into our listing. The remaining moraine categories are bundled in a purely shape-based category *ridge-shaped moraines* that has two subcategories *transverse moraine* and *longitudinal moraine*. The first term is found as a superordinate category to some moraine types in the literature, the latter is not but is introduced for convenience. *End moraine* and *ablation moraine* are subcategories of *transverse moraine*, *lateral* and *medial moraine* of *longitudinal moraine*.

Dune. DIGEST, AFTT and WNET contain categories related to dunes. DIGEST simply defines its category *sand dune/sand hills* as "ridges or hills of sand". Not much more informative is the WNET synset *dune, sand dune* described as "a ridge of sand created by the wind; found in deserts or near lakes and oceans". The synset has a single hyponym *seif dune* defined as "a long and tall sand dune with a sharp crest; common in the Sahara". Clearly, the most extensive definition for dunes is that of AFTT: "low mounds, ridges, banks, or hills of loose, wind-blown granular material, either bare or covered with vegetation, capable of movement from place to place but always retaining their characteristic shape". As opposed to the other two definitions that only talk of "ridges" or "hills" of sand, the latter additionally offers low mound and banks as forms of dunes. The AFTT definition mentions the fact, that dunes may be (partly) covered with vegetation. Generally, all definitions through their use of descriptive form of general nature (e.g. hill) highlight the limited size of dunes (as compared to other topographic eminences such as mountains). The mentioning of ridges implies that there are dunes (dune types) which are elongate rather than of round extent and conical shape.

Summarising, it can be stated that the taxonomy of dunes in the reference works is very shallow (similar to the category *moraine*). Therefore, we referred to additional literature to enrich it. Some authors make a basic distinction into two occurrences of dunes: coastal versus desert (or less clear: sand) dunes (Whittow 2000, Mayhew 2004). The first are "more complex in form (…) owing to plant growth, marine erosion and the presence of groundwater reaching the surface (…)" (Whittow 2000). Also, there is the distinction between aeolian and subaqueous dunes (Lapidus et al. 2003). The latter are a bedform formed in a water current (Kearey 2001) and are not of interest here. Aeolian dunes are made from unconsolidated material, in most cases sand (Allaby and Allaby 1999). However, dune material can also be clay, gypsum or carbonate (Kearey 2001).

The most important dune forms seem to be barchans, transverse dunes, longitudinal or seif dunes, parabolic dunes, draas and star dunes.

Barchans are crescent-shaped mobile dunes in areas where the wind blows mainly from one direction and where there is a sparse supply of sand (Allaby and Allaby 1999, Lapidus et al. 2003). "(…) the convex gentler windward side extends laterally to the two distal 'horns' or 'wings' which curve downwind on either side of the steeper concave slip-face (…)" (Whittow 2000). The height of barchan is given to range from 0.3 to 30 metres (Kearey 2001, Whittow 2000). The angle of the steeper lee side is given as about 32° (Allaby and Allaby 1999, Ahnert 1998), that of the windward side as ranging from 10° for dunes of 3 metres height to 17° for dunes of 8 metres height (Ahnert 1998 for an example in Peru). The distances between horns of barchans measured in Peru are reported to be 8–10 times greater than dune height (Ahnert 1998). Movement rates of barchans are given to be 5–10 metres per year (Kearey 2001) or 10–20 metres per year (Allaby and Allaby 1999). While barchans may occur as isolated features, “they usually occur in groups or belts” (Whittow 2000) their positions often being “staggered so that the horn of one barchan is aligned more or less with the centre of the barchan on its lee side” (Ahnert 1998). With increasing supply of sand barchans can transform over barchanoid dunes into aklé (Fig. 24) and/or transverse dunes or into seif dunes (Lapidus et al. 2003, Mayhew 2004).

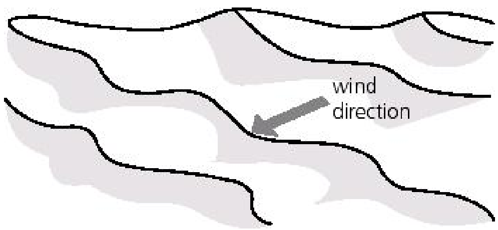


Fig. 24: Aklé dunes (Allaby and Allaby 1999).

Transverse dunes are asymmetrical and at right angles to the prevailing wind direction (Whittow 2000, Kearey 2001). They may develop a regular spacing. Lapidus et al. (2003) subdivide transverse dunes into dunes with straight ridges and sinuous aklé dunes with alternating concave and convex sections. According to Allaby and Allaby (1999), “aklé” refers to “a network of sand dunes found especially in the western Sahara” whose basic unit is “a sinuous ridge, at right angles to the wind (…)”. The phenomenon is equally described by Kearey (2001). We therefore think, aklé dunes can be regarded as subcategory of the ridge-shaped long transverse dunes. According to Allaby and Allaby (1999), transverse dunes “are initial forms on sandy coastlines in temperate regions. They migrate inland and may be eroded locally by the wind to form a damp hollow or ‘dune slack’. The enclosing crescentic dune is a ‘parabolic’ dune whose form reverses that of the barchan.”

A longitudinal (or seif, or sword) dune (Fig. 25) is “knife-edged ridge of sand” (Whittow 2000) aligned with the direction of the prevailing wind. Other sources refer to two alternately prevailing wind directions (Mayhew 2004, Allaby and Allaby 1999). They are long, 10 kilometres or more according to Lapidus et al. (2003), and have a height of up to 100 metres (Kearey 2001) or 200 metres (Whittow 2000). Longitudinal dunes are found in hot deserts (Allaby and Allaby 1999) and commonly occur in groups of parallel ridges

(Kearey 2001). According to Whittow (2000) chains of longitudinal dunes may easily extend over 100 kilometres in length.

Fig. 25: Seif dunes (Allaby and Allaby 1999).

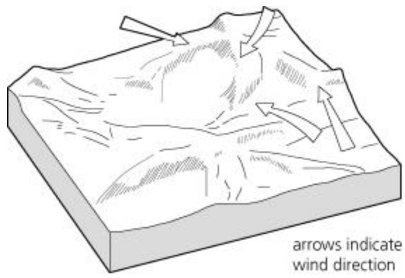


Fig. 26: Star dunes (Allaby and Allaby 1999).

Parabolic dunes are described as resembling barchans but with the horns pointing in the upwind instead of downwind direction.

Draas are another well-known dune type. They are the largest accumulations of sand in the Sahara (Whittow 2000), up to 400 metres in height and with wavelengths of over 650 metres (Lapidus et al. 2003). When draas coalesce they may form star-shaped features called rhourds (ibid., Allaby and Allaby 1999). Because this feature seems to be a local one (restricted to the Sahara) it is not explicitly contained in our landform taxonomy.

Star dunes (Fig. 26) are relatively permanent dunes. They are of pyramidal shape with sand ridges (Whittow 2000). According to Kearey (2001) star dunes are "pyramidal dunes with three arms radiating from a high central dome". However, the number of arms may not be so determinate since Kearey (2001) is the only source that gives this specification. Allaby and Allaby (1999) and Mayhew (2004) state that star dunes develop in areas of highly variable wind directions. Ahnert (1998: 122) mentions "pyramid dunes", "sand mountains" and "ghourds" as alternative names for star dunes. According to him these are the highest dunes of all rising to more than 100 metres, sometimes even to several hundred metres. They may also occur overlaid on linear dunes if there is enough sand supplied.

Some of the aforementioned dune categories seem to primarily occur in hot desert regions such as the Sahara in Africa. Coastal dunes (as opposed to desert dunes) seem more relevant in Europe. Ahnert (1998: 123) states that "in humid regions, dunes are confined largely to coastal areas where there is a sand beach as the source of supply." Coastal dunes are often "at least partially" covered with vegetation that stabilises the dune and thus impedes the movement of sand grains. "Coastal dunes have an irregular shape and are known as kupsten dunes." (ibid.) The irregularity of shape may be the reason why there is a less developed taxonomy in this area. Whittow (2000) also emphasises the irregular nature of the form of coastal dunes but describes a sequence that can be found for coastal dunes: "It is often possible to distinguish a development landwards, from the fore-dune, through the main mobile dune to the stabilized dune." The fore-dune is nearest to the sea and the youngest of the coastal dunes. It is characteristically colonized by a certain grass tolerant against sea water (ibid.). No form descriptions are given. Mobile dunes have half the surface fixed by vegetation but at uncovered parts blowouts can form through deflation. "Thus many coastal dune areas exhibit a mixture of sandy depressions interspersed with mobile dunes in an apparently confused pattern." (ibid.) The most landward dune form is the stabilised dune. It is fixed by vegetation and thus protected from wind action.

Dunes are of a category that is very much defined in terms of material (grains of sand size) and forming process (aeolian) and that is not very coherent in shape. Therefore there are two subcategories to dunes we would like to introduce: *ridge-shaped dune* as subcategory of *ridge* and *hill-shaped dune* as subcategory of *hill*. From the above descriptions we inferred that barchans, transverse (and aklé) dunes, longitudinal and parabolic dunes have all a more or less pronounced ridge character. We thus put them as subcategories in *ridge-shaped dune*. Both star-shaped dunes and coastal dunes seem more like hills in general. However, the form character of the fore-dunes may resemble a ridge as well, since they are aligned along the beach. We put star dunes and coastal dunes as subcategory of *hill-shaped dunes*.

3.4.2 Topographic depressions

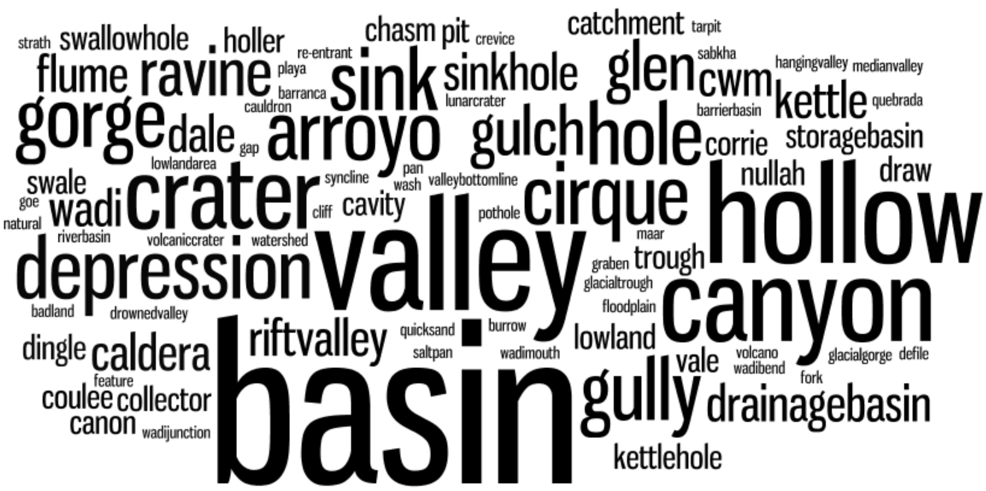


Fig. 27: Tag cloud for the *topographic depressions* listing.

Valley. Valleys are among the most prominent topographic depressions. They are (with the exception of DIGEST which features only *valley bottom line*) contained in all reference works of this study. A valley is described as "depression" (WNET, SDTS), "low area" (OSHO) or "low-lying land" (AFTT, SUMO-G). There are obviously two different conceptions of valleys. While WNET and SDTS have a comparatively narrow view regarding valleys, OSHO, AFTT and SUMO-G feature a broader valley category. The narrow view of WNET and SDTS describe valleys as long depressions possibly (mentioned by either one) narrow, with a fairly regular downslope or usually containing a river. OSHO's definition of a valley ("a low area more or less enclosed by hills") is very much broader – in fact, sufficiently broad to render it useless. SUMO-G defines a valley in a similar way as "(…) an area of low-lying land flanked by higher ground (…)" typically containing a stream or river on the valley floor. AFTT strikes a balance between the two suggesting valleys as "low-lying land bordered by higher ground" but noting that the term "especially" stands for "elongate, relatively large gently sloping depressions of the Earth's surface, commonly situated between two mountains or between ranges of hills or mountains, and often containing a stream with an outlet" – which is quite compatible with the narrower conceptions of WNET and SDTS. Whittow (2000) describes a valley as linear depression, "sloping down towards a lake, sea or inland depression". Lapidus et al. (2003) define a valley as "a linear, low-lying tract of land bordered on both sides by higher land and frequently traversed by a stream or river." The forming agent of all valleys is running water; changes in cross-profile encompass the widening of a V-shaped valley or the formation of a U-shaped valley (by glacial erosion).

We stick to the narrower definition that sees valleys as elongate depressions of the earth's surface, often with a stream or river and a usually gentle, fairly regular downslope. This definition is supported by Whittow (2000) and Lapidus et al. (2003). We think the broader definitions (especially that of OSHO) do not strike the balance between complexity and information content. They are too broad (almost as broad as those for *topographic depression*) so that too many features would be accommodated within them. However, we decided to introduce an artificial category *longitudinal depression* to bundle some of the 'valley-like' categories that will be elucidated later on. With *longitudinal depression* we simply mean an elongate depression of the earth's surface that usually will drain water – as opposed to, for example, bowl-shaped depressions.

V-shaped valley. V-shaped valleys are mentioned in Ahnert (1998 162) as one type of fluvial valley forms (the other being termed *flat-floored valley*). According to Whittow (2000) a V-shaped valley is characterised by "evenly sloping sides and a V-shaped cross-profile". The angle of the valleysides is determined by several factors (after Whittow 2000):

Climate

Humid climate favours rapid mass-movement and thus as a tendency widens the angle.

Resistance of the rock to weathering and erosion

„E.g. valleys cut in cohesive silts or clays (loess) have a tendency to create deeply cut ravines with steep slopes (badlands).“ (ibid.)

Aspect

Shaded and sunny slopes expose different magnitudes of slope processes.

Rate of river vertical erosion

"E.g. a rapid period of uplift will ensure that a narrow V-shape will be maintained." (ibid.)

Location along the stream

"The location of the cross-profile on the long-profile of the river, for in its lower reaches the valley will be extremely broad and its bluffs a great distance apart, thus creating a cross-profile which cannot be described as V-shaped." (ibid.)

The last statement may well refer to what Ahnert (1998: 162) terms *flat-floored valley*. Opposed to the traditional V-shaped valley whose "side slopes (...) border immediately on the channel" (ibid.), in a flat-floored one, there is a valley floor lying between the stream and the valley side slopes. This valley floor "is produced by lateral erosion, accumulation or a combination of the two" (ibid.). According to Ahnert (1998: 162), this characteristic has consequences for the relationship between the valley and the river flowing in it: In a V-shaped valley the orientation of the stream is the same as the one of the valley and their respective lengths are similar. In a flat-floored valley there may be a difference between stream and valley directions since the broad valley floor allows the stream to alter its flow direction with respect to the valley sides or to diverge into several channels. Where these situations occur, it in turn leads to a greater length of the river with respect to the valley.

There can be a transition from gorges (to be elucidated later on) to V-shaped valleys and to flat-floored valleys. This process is described by Ahnert (1998: 214): Since the depth of gorges is limited by the critical height of their rock walls, exceeding this critical height leads to rock falls and landslides and thus to the development of a V-shaped valley with steep valley sides and limited denudation. “This state lasts as long as the rate of downcutting is greater than the maximum possible rate of retreat of all parts of the slope by weathering and denudation.” (ibid.) When vertical erosion stops, the valley becomes a flat-floored one.

Although the categorisation by Ahnert (1998) of fluvial valleys into V-shaped valleys and into flat-floored valleys is to some extent, of course, gradual, we deem it possibly quite interesting and important in regard to the extraction of such landforms. We thus decided to integrate both fluvial valley forms as separate categories into our taxonomy.

Glacial valley/trough. The second prominent valley category is that of glacial valleys or glacial troughs. Glacial troughs are featured as an included type in the *valley* category of SDTS. Besides, there are other occurrences of the term *trough*: once more in SDTS (however, not as included type but as a distinct category: “a long depression of the sea floor” and in WNET (“a narrow depression (as in the earth or between ocean waves or in the ocean bed)”). However, both terms do not relate very much to the meaning of *(glacial) trough* we are discussing.

The terms *glacial trough* and *glacial valley* are sometimes used synonymously with *U-shaped valley*: for instance, in the definition by Whittow (2000) “a valley that has been overdeepened by glacial erosion and which is termed a U-shaped valley”. However, in her definition of the term *glacial trough* Mayhew (2004) states: “Once termed U-shaped valley, this is a wide valley floor with steep sides formed by glacial erosion. (...) The shape of a glacial trough more resembles a parabola than the letter U.” Consequently, the term *U-shaped valley* is seldom found in the literature we used. It is featured in Whittow (2000) who equates it with a glacial trough and in Mayhew (2004). The latter definition brings in a new aspect: “Most U-shaped valleys – valleys with a parabolic cross-section – are glacial troughs. However, valleys with this form are also encountered in non-glaciated chalk topography.” (ibid.) These latter features are not mentioned in other literary sources.

Ahnert (1998: 270) states that glacial troughs are, in fact, glacier beds, whose boundary is the trough shoulder which “usually appears as a distinct zone in the slope profile lying above the steep slopes of the trough itself”. Besides their U-shaped or parabola-shaped cross-section and the trough shoulders, glacial valleys or troughs are characterised by hanging valleys and truncated spurs (Whittow 2000), relative straightness (with respect to fluvial valleys; Lapidus et al. 2003, Mayhew 2004), steep sides and often irregular long-profiles with rock barriers, steps and basins or basin lakes (Allaby and Allaby 1999, Mayhew 2004; “trough basin lakes” in Ahnert 1998: 270; when occurring in a series “pa-ternoster lakes” in Huggett 2007: 254). Rock barriers may be caused by zones of more resistant rock. “Today streams cross the barriers in narrow chasms that were usually first eroded subglacially by meltwater streams.” (Ahnert 1998: 271). Steps can be caused by several factors such as confluence of glaciers leading to an increase in vertical erosion, varying rock resistance or the presence of pre-glacial knick points. Some large troughs in the Alps have effectively become flat-floored due to sediment fill. Specifically, Ahnert (ibid.) mentions the Inn and Rhône valleys.

As to size, according to Lapidus et al. (2003) glacial valleys can be several hundred metres deep. Allaby and Allaby (1999) state the world’s largest glacial valley to be that of the Lambert Glacier in Antarctica. This valley is 50 kilometres wide and approximately 3.4 kilometres deep.

We put glacial troughs into a distinct *valley* subcategory, for they differ in a number of aspects from the other valley subcategories elucidated thus far.

Hanging valley. Hanging valleys are often (probably nearly always) glacial features. They are always glacial features in an indirect way. Kearey (2001), for instance, states as definition: “a tributary valley whose floor is at a higher level than the main valley, caused by the latter’s deepening by glacial erosion”. According to Whittow (2000) the hanging valley is a “tributary valley debouching at an elevation distinctly higher than that of the floor of the glacial trough in either a glacierized or glaciated terrain.” In their description of glaciated valleys Lapidus et al. (20003) state that “smaller, shallower troughs are cut by smaller tributary glaciers. When the glaciers melt, they remain as hanging valleys on walls of the glacial valley.” However, Allaby and Allaby (1999) and Mayhew (2004) suggest that not only glacial troughs can be hanging valleys. The first authors write that hanging valleys are “typical of glaciated uplands, where [they] may result from glacial widening and/or deepening of the main valley”. Mayhew (2004) states: “The depth of the lower valley may be attributed to more severe glaciation (...). Some writers suggest that these features are caused by two phases of glaciation separated by a period of fluvial erosion, or that the erosive power of the tributary stream has been less than the erosive power of the larger stream; glaciation may not be the only process involved". But is it always involved and does it transform the tributary, hanging valley into a glacial one? This remains unclear, however, the hints in the afore-mentioned texts forbid the conclusion that hanging valleys need to be glacial troughs. One special case of non-glacial hanging valleys (that is described e.g. in OED) is refuted, however, by Whittow (2000): "In the cases where marine erosion has truncated normal stream valleys by a series of sea cliffs and where the streams may descend to the sea in the form of waterfalls, the term hanging valley is not really appropriate."

However, the possibility that different kind of valleys can be a hanging valley is a clear hint (and effectively a consequence of the fact) that the term *hanging valley* is defined in a relational manner. That means that a valley is termed a hanging valley only by relating it to another ("main") valley it leads into. That a valley is a hanging valley is thus not a characteristic of the valley itself; for we would conclude from the above-mentioned statements that the steep part connecting the hanging valley to the floor or stream in the main valley is not part of the hanging valley itself but rather part of the valley sides of the main valley. This considerations imply that a feature termed *hanging valley* can always be accommodated in another *valley* subcategory, since *hanging valley* only refers to a special relational property of the valley to another valley and not to more intrinsic form properties of the valley (i.e. *hanging valley* can be considered a role a valley adopts; similar to the case of *foothill* for a hill). We thus do not regard *hanging valley* as a self-dependent subcategory of *valley*.

Rift valley. Rift valleys are another type of valleys. They are contained in WNET (as a hyponym of *valley, vale*) and in SDTS (as an included type of *valley*). WNET defines a rift valley as "a valley with steep sides; formed by a rift in the earth's crust". More extensive definitions come from our other sources. Whittow (2000) defines a rift valley as "a linear depression or trough created by the sinking of the intermediate crustal rocks between two or more parallel strike-slip faults. The structure is known as a graben and the accompanying morphological feature as a rift valley. (...)" With SDTS only one source work contains *graben* as a feature, namely as an included type of the *valley* category. This is misleading considering Whittow's (2000) statement above. Also, Allaby and Allaby (1999) implicitly support Whittow's (2000) assertion, stating that "graben (the German word for 'ditch') can be used synonymously for 'rift valley' and also for an infilled, fault-bounded trough of any size, with or without topographic expression". Besides, they define a rift valley as "an elongate trough, of regional extent, bounded by two or more faults. (...)" However, it remains unclear what they mean by "regional extent". Lapidus et al. (2003) describe a rift valley as "an elongate topographical depression bounded by steep-dipping parallel or subparallel faults that have large dip-slip component (...)." According to Huggett (2007: 143), "rift valleys are not true valleys and they are not all associated with linear depressions." Rift valleys are often associated with volcanic activity and the occurrence of earthquakes. The Rhine rift valley is an example of an isolated occurrence, while the rift valleys in the Aegean extensional province, Greece, lie in graben fields and "form many, nearly parallel structures" (ibid.).

Several examples are given for rift valleys. Whittow (2000) mentions a range of rift valleys of varying magnitude "from those of the mid-oceanic ridges, and the Red Sea graben, to the East African Rift and the Rhine graben. Almost all are associated with vulcanicity (...)". The Rhine rift valley is indicated to have a length of 280 km. The East African rift system and the Rhine rift valley are also mentioned by Lapidus et al. (2003) and Allaby and Allaby (1999), while the latter also describe Tibetan rifts. The East African rift system is termed "the biggest terrestrial rift valley system (...) at 3000 km long" (Mayhew 2004). The East African rift valley (or the Great Rift Valley of East Africa) is actually only a part of a larger structure together with the Red Sea and the Levant (Huggett 2007: 143). Besides, there is the Valle de Cibão Graben, Hispaniola, that has a length of 250 km and a width of up to 40 km, "roughly the same as the Rhine rift valley" (ibid.).

Though rift valleys may be quite difficult to distinguish from other valley types (e.g. very broad fluvial valleys) we think due to their very distinct origin they represent an important category. We thus include a *rift valley* category in our listing as a subcategory of *valley*.

Dale, glen, hollow, holler. The category *dale* is in WNET a hyponym of *valley, vale* and is characterised as "an open river valley (in a hilly area)". The category of dales is also listed as included type in the *valley* category in SDTS, however, of course without a definition. Thinking about the notion of "dales" James Clerk Maxwell's (1870) publication "On Hills and Dales" comes to one's mind. In this seminal publication Maxwell (1870: page 238 of the reprint) equates dales with (drainage) basins. This sense of *dale* cannot be found in modern geomorphology literature, however. None of the geomorphology, geology or geography works we used (Allaby and Allaby 1999, Whittow 2000, Kearey 2001, Lapidus et al. 2003, Mayhew 2004) contained the category *dale*. OED, however, distinguishes two meanings for *dale*. Firstly, there is the now obsolete meaning: "a hole in the ground, a hollow, pit, gulf'. Secondly, *dale* can be used to denote a valley. *Dale* is "in the northern counties, the usual name of a river-valley between its enclosing ranges of hills or high land. (…)". The term can still be found in geographical names and it can also be used figuratively. However, OED points out that *dale* is "in literary English chiefly poetical, and in the phrases hill and dale, dale and down". We therefore conclude that *dale* has to a large degree lost its geomorphologic relevance, is only very vaguely separated from other categories and we hence exclude it from our taxonomy.

Glen is in WNET a hyponym synset of *valley, vale*, as well. However, it is not broadly used, either. WNET defines it as "a narrow secluded valley (in the mountains)" while Whittow (2000) reads: "a Scottish term for a steep-sided valley in the Highlands. It is narrower than a strath", the latter in turn being defined as broad, flat-floored river valley. Indeed, *glen* is adopted from the Gaelic *gleann* (OED). Whittow's definition takes quite a narrow view of the category, virtually constraining it to be applied in the area of the Scottish Highlands. This view is contrasted by OED which characterises a glen as "a mountain-valley, usually narrow and forming the course of a stream. At first applied to the narrow valleys of the mountainous districts in Scotland and Ireland, but now extended to similar places in other countries." However, the few mentions in geomorphologic reference works suggest the use of the term has not broadened much. Additionally, it does not seem to convey more information than *valley* or possibly *valley in a mountainous region*. Thus, we decide not to feature this category in our taxonomy.

The hyponym (to *valley, vale*) synset *hollow, holler* is characterised in WNET as "a small valley between mountains". *Hollow* is also a category in OSHO and is there defined from the hydrologic viewpoint as "an empty space" with three sub-kinds: basin, channel and pipe. *Hollow* in that sense could maybe equated with a container. It also relates to the WNET synset *hole, hollow* defined very generally as "a depression out of solid matter" with such diverse hyponym synsets as *burrow, tunnel*, *gopher hole*, *kettle hole, kettle*, *pit, cavity*, *pothole, chuckhole*, *rabbit burrow, rabbit hole* and *wormhole*. These latter notions of *hollow* are either characterised from a too narrow viewpoint (hydrology in OSHO) or are of too general nature (WNET) to be useful. And, most importantly they refer to a different meaning of hollow than in the synset *hollow, holler*. OED defines *hollow* in two ways; generally, as "a hollow or concave formation or place, which has been dug out, or has the form of having so been" and more specifically, among several obsolete and alternative meanings as "a surface concavity, more or less deep, an excavation, a depression on any surface" and also as "a depression on the earth's surface; a place or tract below the general level or surrounded by heights; a valley, a basin." As expected, the second part of the synset – *holler* – is indicated as a variant of *hollow* in that last meaning. However, OED indicates that *holler* is colloquial in the USA. Indeed, the OED definitions for *hollow* and *holler* do not match the definition given by WNET, the latter being definitively more specific. For reasons of consistency with above decisions regarding *dale* and *glen*, we decide not to feature *hollow* either because of its limited information content.

Ravine, gully. The synset *ravine* is another hyponym of *valley, vale*. WNET defines a ravine as "a deep narrow steep-sided valley (especially one formed by running water". The category is picked up by Whittow (2000) and – indirectly by Allaby and Allaby (1999; writing about "ridge-and-ravine topography"). Whittow's (2000) characterisation – "a deep narrow river valley but without the precipitous sides of a gorge, which it resembles in stature. It is bigger than a gully." – relates ravines to gorges and gullies. *Gully* is contained in WNET and in combination with *gorge* in DIGEST and is defined as a "deep ditch cut by running water (especially after a prolonged downpour)" and as "a long, narrow, deep erosion with steep banks", respectively. Whittow (2000) defines a gully as "a small but deep channel or ravine formed by fluvial erosion but not permanently occupied by a stream" thus implying gullies can be a kind of ravines. Kearey (2001) explains gully erosion as "the erosion of steep-sided channels and small ravines in poorly consolidated material or bedrock (…)". Additionally, Allaby and Allaby (1999) state that gullies can develop on valley sides and along valley floors. In the later case they call them "arroyos". However, this view is not explicitly supported by other references. Huggett (2007: 221) says that rills – "a few centimetres wide and deep" – grade into gullies – an arbitrary lower limit for the latter being a third of a metre wide and two-thirds of a metre deep. According to Huggett (ibid.), "gullies are intermediate between rills and arroyos, which are larger incised stream beds." However, later on Huggett (ibid.) defines arroyos as "ephemeral stream channels in arid and semi-arid regions". As to the location of gullies, Mayhew (2004) writes that gully erosion is "the removal of topsoil and the creation of many steep-sided cuttings in a hillside". Also Ahnert (1998: 115) points out the importance of the steepness of a surface for the formation of rills through rill wash (as opposed to sheet wash) and states that gullies are both deeper and larger than rills, "eroded into the saprolite, sometimes down to the bedrock, "their steep side slopes generally reflect[ing] the maximum possible slope angle of the material".

Summarising, both gullies and ravines are somehow intermediates of small channels or rills and gorge-like valleys. They tend to occur in unconsolidated rock rather than in bedrock (Mayhew 2004) and may very well occur on hillsides – and thus possibly with a relatively high longitudinal gradient when compared to common valleys. Since the discrimination between the following: ephemeral stream channels and rills – gullies – ravines – valleys, may be qualitative, we consider it superfluous and undesirable for reasons of simplicity to include both, the gully and the ravine category independently. Terminologically, we deem *gully* more popular than *ravine* according to the number of mentions in our literary sources (e.g. ravines are featured neither in Ahnert (1998) nor in Huggett (2007)). However, on the other hand gullies rather than ravines are probably not detectable using coarser DEMs. We thus decide to incorporate *gully, ravine* into our taxonomy, meaning a relatively small (in relation to ordinary valleys), steep-sided longitudinal depression possibly found on hillslopes and not usually occupied by a permanent stream. Despite some conflicting properties due to the possibly relatively high gradient of gullies or ravines as opposed to the usually gentle, fairly regular downslope of valleys, we think the *gully, ravine* category can be comfortably put as a subcategory to *valley*.

Arroyo, draw, wadi, (dry) wash, coulée/coulee, nullah. The term *arroyo* that has already occurred in the description of gullies and ravines is featured in WNET ("a stream or brook") and in AFTT ("small deep flat-floored channels or gullies of an ephemeral stream or of an intermittent stream, usually with vertical or steeply cut banks") only. In WNET *arroyo* is a hyponym of *gully* and has siblings *draw* and *wadi*. Generally, it is thought that arroyos occur "in deserts" (Kearey 2001) or "in an arid or semi-arid region" (Allaby and Allaby 1999). Ahnert (1998) does not describe arroyos, while Huggett (2007: 221) relates them to gullies (see the respective section above) and equates them to wadis, washes, dry washes, and coulees. OED says an arroyo is "a rivulet or stream; hence, the bed of a stream, a gully" and that the term is from Spanish and used in the USA. We decide not to use *arroyo* since it seems to be used primarily in the Americas and since we think it can be adequately substituted with the category *gully, ravine*.

The same goes for the terms *draw* and *wadi* (alternatively *ouady*, *oued*, *wady* according to Kearey 2001). WNET regards both *draw* and *wadi* as a hyponym of *gully* and defines the first one as "a gully that is shallower than a ravine". Kearey (2001) has two meanings for the term; firstly, very unspecifically "a natural linear depression followed by surface drainage", and secondly – strongly contradicting WNET, "in the USA, a dry watercourse in the shape of a deeply incised ravine, occupied seasonally by an ephemeral stream." On the other hand, WNET defines a wadi as a "gully or streambed in northern Africa and the Middle East that remains dry except during rainy season". Besides, a wadi is characterised as "a steep-sided watercourse with sporadic flow in an arid region" by Kearey (2001) or as "in a hot desert, a steep-sided, flat-floored valley very occasionally occupied by an intermittent stream. (…)" (Mayhew 2004). AFTT, on the other hand, recommends using the term *arroyo* for *wadi* and all parts or segments of wadis. However, we decided not to use the categories *draw* and *wadi* at all (primarily for reasons of redundancy and in the case of *draw* a seemingly very vague meaning), subsuming potential instances in the *gully, ravine* category.

The term *wash* or *dry wash* is only indirectly contained in the source works; AFTT suggests using *arroyo* for *wash*. However, as stated before, Huggett (2007: 221) also equates washes (and also coulees or coulées) to arroyos. Furthermore, Kearey (2001) refers to arroyo for washes, while Whittow (2001) features four different meaning for the term, in particular: „a US expression for a shallow streamless channel in the arid and semi-arid lands of the SW USA“. OED as well highlights the U.S. origin of the term. We thus decided not to use this term in our taxonomy.

Coulée (sometimes *coulee*) also seems to be a U.S. term. Ahnert (1998) does not feature the term, Whittow (2000) mentions among other meanings "occasionally applied to a gorge-like stream valley in the USA". Besides this meaning there are other geomorphologic connotations of *coulée*: that of a lava flow (e.g. Lapidus et al. 2003, Allaby and Allaby 1999) and that of glacial meltwater channels (e.g. Whittow 2000, Lapidus et al. 2003). Thus, in geomorphology, the term *coulée* is ambiguous, the meaning related to lava flows being more popular than that of a (U.S.) ephemeral stream channel. We thus decided not to use this term either.

WNET features *nullah* as a hyponym of *valley, vale* and thus as a sibling of the synsets *gully* and *ravine*. This is somewhat curious, since the definition of *nullah* by WNET is indeed "a ravine or gully in southern Asia". While Whittow (2000) contrasts this with the characterisation "a normally dry watercourse in India, filled only temporarily during the monsoons" the other reference works do not feature this category at all. Hence, we assume that the term is mostly (maybe even exclusively) used in southern Asia and that its meaning is subsumed to a sufficient degree in the *gully, ravine* category.

Gorge, canyon, gulch, flume. A category of gorges is contained in SDTS, WNET, and DIGEST. OSHO and SUMO-G do not list this category. However, SUMO-G contains a category *canyon* that will be discussed subsequently in this section. In SDTS *gorge* is an included type in the *valley* category – though, no definition is given. WNET defines a gorge as “a deep ravine (usually with a river running through it)”, while DIGEST describes its category *US-gully/gorge* as “a long, narrow, deep erosion with steep banks”. AFTT recommends using *canyon* for gorges.

Lapidus et al. (2003) define a gorge as “a deep, narrow, steep-walled valley, sometimes carved by stream abrasion. It may also be a narrow passage between hills or mountains.” Mayhew (2004) writes: “a deep and narrow opening between upland areas, usually containing a river. (...)”. Huggett (2007) differentiates gorges in karst areas and along coasts. Rivers erode gorges more frequently in karst than in other areas (Huggett 2007: 202). This is because river incision is stronger than slope erosion in these places. Thus no V-shaped cross section can develop. In relation to coastal landscapes Huggett (2007: 325) describes a gorge as “a narrow, steep-sided, and often spectacular cleft, usually developed by erosion along vertical fault planes or joints in rock with a low dip”. Ahnert (1998: 214) mentions what they term *saw cut gorge* as one extreme of the relations of vertical river incision and denudation of the slopes which determine “the ratio between valley depth and valley width”. Saw cut gorges are only as wide as the stream they contain. They are frequent in high mountain areas that were glaciated during the last ice ages. In such areas glaciers sometimes produced what is termed hanging valleys. At the steps between these hanging valleys and lower main valleys, gorges “with steep gradients” (Ahnert 1998: 214; cf. also 271) could develop. Still according to Ahnert gorges can only develop in resistant rock, their depth effectively being limited by the critical height of the rocky side-walls.

Canyon is contained in WNET, AFTT and SUMO-G. In WNET *canyon* is (along with *gorge*) a hyponym of the *ravine* category. Accordingly, WNET defines a canyon as “a ravine formed by a river in an area with little rainfall”. This is quite distinct from the other two definitions: “relatively narrow, deep depressions with steep sides, the bottom of which generally has a continuous slope” (AFTT) and “a canyon is a narrow valley with steep sides, usually created by erosion” (SUMO-G). AFTT suggests the use of *canyon* instead of (among others) *gorge* and *ravine*. Allaby and Allaby’s (1999) definition is similar to these except that they put *canyon* as subcategory to *gorge*: “a deep, steep-sided gorge cut by a river, generally into bedrock.” Lapidus et al. (2003) state a similar definition: “a deep, steep-walled gorge cut by a river or stream, generally into bedrock. (...)”.Similar to WNET they state (ibid.), that canyons are "most frequently found in arid or semi-arid regions where the effect of stream action greatly outweighs weathering", a necessary condition for the deepness combined with relatively narrow widths of canyons. Mayhew (2004) makes a clear distinction between canyons and gorges: "an extreme type of v-shaped valley with very steep sides and no valley floor. A canyon differs from a gorge in that the sides are stepped, reflecting alternating rock resistances. (…)" She mentions the Grand Canyon of the Colorado River as the most famous example. Whittow (2000) states: "(...). The most striking canyons are produced in areas of horizontally bedded strata where alternating treads and steep risers are characteristic (e.g. the Grand Canyon, USA)." (ibid.). Thus, Whittow (2000) also highlights stepped sides of canyons. However, what distinguishes his definition from that by Mayhew (2004) is that these stepped sides are only optional features of canyons. Whittow (2000) explicitly mentions the Grand Canyon in the USA as an example of a canyon with stepped sides. Indeed, the term *canyon* is American. Its origin is the Spanish *cañon* (meaning *tube*, *pipe*, *conduit*, *barrel* or *cannon*) which was used by the Spaniards of New Mexico and later adopted by English-speakers in the form *canyon*. Canyons are "characteristic of the Rocky Mountains, Sierra Nevada, and the western plateaus of North America" (OED). We here adopt the view that we can substitute the term *canyon* by *gorge* neglecting the (minority) view of Mayhew (2004) that the former distinguishes itself from the latter by stepped sides; the perception of the stepped sides as being characteristic may be an artefact produced by the frequent reference for the term *canyon* to the Grand Canyon. We regard *gorge* as a subcategory of *valley*, that defines itself through the following characteristics: it is steep-sided, relatively narrow, with a high depth-to-width ratio. If it contains a stream, the stream covers more or less the complete width of the feature, i.e. there is no floodplain or extended valley floor.

In WNET the *gorge* category has a hyponym synset *gulch, flume*. *Gulch* is an included type of the *valley* category in SDTS. AFTT recommends the use of *canyon* for features like gorges, gulches, and flumes. The term *gulch* is not widely used (i.e. not mentioned in e.g. Kearey (2001), Lapidus et al. (2003), Allaby and Allaby (1999), Mayhew (2004), Ahnert (1998), Huggett (2007)). Whittow (2000) characterises it as "a deep ravine in the SW of the USA" and refers to arroyos, creeks and washes. OED states that the term is indeed of U.S. origin and that it denotes (as one meaning) "a narrow and deep ravine, with steep sides, marking the course of a torrent; especially one containing a deposit of gold". This is quite compatible with WNET ("a narrow gorge with a stream running through it"). The second term, *flume*, is wider known. It is defined as, for example, "a deep, narrow gorge containing a turbulent stream" (Kearey 2001) or "a deep narrow gorge in the USA, in which the stream flows in a series of rapids and cascades" (Whittow 2000). Lapidus et al. (2003) is quite compatible with Whittow (2000). Mayhew (2004) and Allaby and Allaby (1999) refer to a flume either as an artificial or an experimental channel – this meaning also being mentioned by Whittow (2000). Ahnert (1998) and Huggett (2007) do not feature the term. Both terms are not very widely used and are more or less constrained to the USA. In the case of *flume* there is a dual meaning: one denoting a landform closely connected to a gorge, one referring to a human-made device. We thus conclude not to use these two terms but instead the *gorge* category which covers them quite well.

Basin. The term *basin* is contained in SDTS ("any bowl-shaped depression in the surface of the land or ocean floor"), OSHO ("a hollow bowl-shaped depression in the ground, completely bounded at its sides and base by land, that can enable the containment of water"), AFTT ("bowl-shaped, natural depressions in the surface of the land or ocean floor"), SUMO-G ("a basin is an area of land enclosed or partially enclosed by higher land") and WNET ("a natural depression in the surface of the land often with a lake at the bottom of it"). The first three of these definitions are remarkably compatible. The definition by SUMO-G is similarly broad (and similarly useless) to the definition of valleys by OSHO (see above in this section). The one by WNET is not better, the only specific point being the potential presence of a lake. For other authors a basin is a "depression, usually of considerable size (...)" (Allaby and Allaby 1999), or a "major relief depression (...)" (Mayhew 2004). We prefer to adhere to the quite general definition of AFTT or SDTS. The definition by OSHO is quite tempting since it enumerates the capability of holding water as a criterion for basins. This property would render it easier to detect such features in a DEM. However, in this point the definition differs from, for instance, that by Whittow (2000) which reads: "a large sediment-filled depression, enclosed by higher land, with or without an outlet". However, this difference may be in any event a gradual one: imagine a bowl shaped depression with a rim of varying height. Such a feature would be able to hold some water or sediment; however, it cannot be filled up to the maximum height of the rim, since in such a situation water would find an outlet somewhere (the lowest part of the rim). Thus we cannot sensibly enforce any basin to have no outlet at all or to be capable of holding water. However, we think that (most) landforms that can be called basins are capable of holding some water and/or sediment. Besides, an important characteristic of basins is their more or less compact shape (i.e. they are not elongate as e.g. instances of the *valley* category) and their considerable extent (distinguishing them from e.g. small pits and holes such as sinkholes). So, we regard the *basin* category more or less as a container category for compact-shaped, bowl-shaped depressions of considerable extents which are similar to those of *longitudinal depression* that holds subcategories like *valley*.

Besides *basin* there are related terms in the source works: *storage basins*, *drainage basins* (both in AFTT), *river basin, basin* (WNET) and *catchment* (SDTS). Storage basins are defined as "basins in which drainage water is naturally detained" (AFTT). So they resemble very much basins (as we have just defined them), however, they are not only potentially capable of storing water but do actually store drainage water. However, this distinction is of no use to us. The categories of drainage basins, river basins and catchments (or watersheds in the American sense) are well defined and known and do not need to be clarified further here. Although, of course, drainage basins are important features in hydrologic research and applications, we doubt the usefulness of these entities in our context of describing landscapes in terms of landforms. Hence, we do not explicitly include drainage basins and the like in our taxonomy. However, we will well apply the concept in Chapter 4, since drainage basins have an interesting relation to valleys.

Cirque. There is a relatively good agreement between the definitions of *cirque* in the source works. The category seems to be unusually well-defined, along the lines: "a steep-walled semicircular basin in a mountain; (...)" (WNET); "a deep natural hollow near the crest of a mountain" (SDTS); "bowl-like hollows partially surrounded by cliffs or steep slopes (...)" (AFTT), "a French term which has been universally adopted to describe a glacially eroded rock basin with a steep headwall and steep sidewalls, surrounding an arm-chair-shaped depression. (...)" (Whittow 2000). A cirque is indeed a basin-shaped depression and we thus put it as a subcategory of *basin*. Cirques can contain small cirque glaciers or lakes termed *tarns*. "Most small lakes at high altitudes in the Alps are cirque lakes" (Ahnert 1998: 270). Cirques "vary greatly in size" but do maintain proportions surprisingly well: length-to-height ratio of 3:1 (Whittow 2000) or [2.8–3.2]:1 (Huggett 2007: 261). Cirques are also known as corries or cwms (Allaby and Allaby 1999). Since cirques start as depressions where snow accumulates, they are mainly found on the leeside of mountains, where snow accumulation is facilitated. Thus "(...) cirques in the Northern Hemisphere tend to face north and east" (Huggett 2007: 261). According to Mayhew (2004), cirques may measure up to 2 kilometres across. However, Huggett (2007: 261) mentions the largest known cirque to be 16 kilometres wide and 3 kilometres high. They grow by headward expansion, eroding back into the mountain mass. Cirques usually occur "high on a mountain slope" (Lapidus et al. 2003; a view also reflected in the SDTS definition) or in "glacially eroded uplands" (Mayhew 2004). However, in areas that were completely under glacier ice there are no cirques (ibid.).

Crater, collector. A *(volcanic) crater* category is contained in WNET (twice), SDTS and AFTT. Moreover, WNET contains a category *collector* that is a hyponym of *crater* – besides *lunar crater*, which is not considered here (see Section 3.2.8). The synset *crater* is defined by WNET as "a bowl-shaped depression formed by the impact of a meteorite or bomb". It is a hyponym of *(natural) depression*. *Volcanic crater, crater*, however, is defined as "a bowl-shaped geological formation at the top of a volcano". This is a hyponym of *(geological) formation* and a meronym, i.e. a part, of *volcano*. SDTS possibly subsumes the two WNET categories in one category *crater*, characterised as "a circular-shaped depression at the summit of a volcanic cone or on the surface of the land". It is unclear whether SDTS refers to craters of volcanic origin only (which potentially can be "on the surface of the land", too) or whether it implicitly includes craters of cosmic (i.e. meteorite) origin. AFTT makes this explicit describing craters as "circular-shaped depressions at the summit of a volcanic cone or on the surface of the land caused by the impact of a meteorite; man-made depressions caused by an explosion". We think there is no point in an *a priori* distinction of craters of different origin. We thus define a crater as a bowl-shaped depression at the summit or on the flanks (Lapidus et al. 2003) of a volcano, or on the land surface. Craters usually have a circular footprint (Kearey 2001, Allaby and Allaby 1999) and steep walls (in uneroded state) (Whittow 2000, Lapidus et al. 2003). According to Whittow (2000) volcanic craters can be several hundred metres in depth. As to the *collector* category which is defined by WNET as "a crater that has collected cosmic material hitting the earth" we deem it not relevant for our context, since it defines a special kind of a crater which offers a very particular affordance.

Polje, uvala, doline, ponor, sink-hole, swallow-hole. There are a remarkable range of karst (i.e. limestone) depressional landforms which, surprisingly, are not at all contained in any of the source works. First of all, there is the term *polje* denoting "a large, commonly flat-floored, closed depression in a karst area, of equivocal origin" (Kearey 2001). Lapidus et al. (2003) describe it as "a steep-sided enclosed basin with a flat floor (...)" whose "(...) location and orientation (...) appear to be controlled by structural features like faults and fold hinges or contact with an impermeable horizon". Mayhew (2004) also highlights that "most poljes are aligned with underlying structures such as folds, faults, and troughs". Most authors characterise the feature similarly to Lapidus et al. (2003) as a flat-floored (e.g. Allaby and Allaby 1999, Mayhew 2004) depression or basin bounded by steep sides or walls (ibid.). OED, however, terms it "an enclosed plain in a karstic region". Indeed, *polje* is Serbo-Croatian for *field*, *plain* (ibid.) As for the size of poljes, Lapidus et al. (2003) state areas from 2 km^2 up to 400 km^2, whereas Mayhew (2004) mentions lengths of up to 65 kilometres and widths of up to 10 kilometres. It is noted, that Kearey (2001) describes poljes as closed depressions and that Mayhew (2004) highlights the fact that "usually the water drains into streamsinks". So, apart from their apparently at least sometimes elongate shape, poljes seem to be bowl-shaped insofar, as they should be capable of holding some water and/or sediment. Nevertheless, we hesitate to simply put them into the *basin* category. The aspect of potentially structural origin and thus predominant orientation along structures is a strong counter-argument. We suggest poljes do have features of both the *basin* and the *longitudinal depression* categories (e.g. potentially partial surface drainage) and we thus put them somewhat ambiguously as a subcategory of both.

Another karst depressional landform is the uvala. The term is from Serbo-Croatian and simply means *hollow* or *depression* (OED). It is virtually unambiguously defined as depression (only Allaby and Allaby 1999 term it a hollow). According to Kearey (2001) uvalas are closed depression; however, this point is not picked up elsewhere. Whittow (2000) highlights the irregular floor of a uvala. This would make it distinct from a polje. Uvalas are formed by the coalescence of two or more dolines (these features will be discussed next; e.g. Lapidus et al. (2003), Whittow (2000), Allaby and Allaby (1999)). As to size there are differing indications: Whittow (2000) writes of "several km in diameter", while Allaby and Allaby (1999) state the diameter to be generally 500–1000 metres and the depth 100–200 metres. Mayhew (2004) notes that "the size of the hollow is not important in the recognition of a uvala". Again, this surface depression seems to have some aspects of a basin, however, it appears to sometimes feature a quite irregular floor which makes it deviate from a bowl-shape. Other than for poljes, there is no hint in the above descriptions of uvalas that they tend to be elongate features. However, both Ahnert (1998) and Huggett (2007) state that uvalas are elongate or lobate depressions. According to Huggett (2007) elongate uvalas (similarly to poljes) follow strike or fault lines. Thus we put the category of uvalas into the same relation with *basin* and *longitudinal depression* as the *polje*.

Further, dolines and ponors are karst depressional landforms. According to OED, the term *doline* is an adaptation of the Russian *dolína* meaning *valley* or *plain*. A doline is described as, for example, “a circular to oval, simple closed depression (...)” (Kearey 2001) or as “a bowl, cone or well-shaped depression” (Lapidus et al. 2003). They develop by solution of limestone, by subsidence or by the collapse of cave roofs (Lapidus et al. 2003, Mayhew 2004). The size descriptions vary between authors: While Whittow (2000) mentions diameters of 10–100 metres, Mayhew (2004) states them as 10–1000 metres and the depth to be 2–10 metres.

Kearey (2001) equates the doline to a shakehole while Whittow (2000) states that a doline “is usually the site at which a stream disappears underground” and in this context refers to sink-holes and swallow-holes. Allaby and Allaby (1999) equate a doline to a swallow-hole and a sink-hole, as well.

Ponor is not contained in many reference works (e.g. Lapidus et al. 2003, Allaby and Allaby 1999, Mayhew 2004). Kearey (2001) defines a ponor as “a sinkhole or swallow hole found in a limestone area”. Whittow (2000) states: “the Serbo-Croat name for a swallow-hole, albeit some authors restrict its use to a deep swallow-hole in a polje”. The term is from Serbo-Croatian and means *chasm*, *abyss* (OED).

The term *sink-hole* (or *sinkhole*, *sink hole*) is defined ambiguously. Kearey (2001) uses the strict definition of “an approximately circular depression in limestone terrain into which water drains and collects”. By contrast, Whittow (2000) states: “It is usually dry or exhibits only minor seepage of surface water and should be distinguished from a swallet, which marks the disappearance of a surface stream.” Whittow (ibid.) explicitly equates *sinkhole* to *ponor*. Lapidus et al. (2003), however, refer to *doline* for their first meaning of *sinkhole*. Allaby and Allaby (1999) know only one meaning and for this they too refer to *doline*. Mayhew (2004) differentiates: “in limestone topography, a roughly circular depression into which drain one or more streams. It is known in Britain as a swallow hole and sometimes used as a synonym for a doline.”

Swallow-hole (or *swallet*) is less ambiguous: Kearey (2001), Whittow (2000), Lapidus et al. (2003) and Mayhew (2004) all highlight the fact that in swallow-holes surface water (or streams) disappear underground. Whittow (2000) says the term is synonymous with (among others) *ponor* and mentions the term *pot-hole* sometimes used in Britain for swallow-holes with spectacular shafts. In contrast, Lapidus et al. (2003) and Allaby and Allaby (1999) refer to *doline*.

The synset *sinkhole, sink, swallow hole* is contained in WNET (as opposed to *doline* or *ponor*). It is defined as "a depression in the ground communicating with a subterranean passage (especially in limestone) and formed by solution or by collapse of a cavern roof". This definition encompasses most descriptions of sink-holes and swallow-holes above. OSHO's definition of *sink*, however, has higher demands explicitly defining it as "a place where a surface water course disappears underground. (...)".

We conclude that the differentiation between the *doline* and *ponor* category is rather gradual, ponors possibly being smaller than dolines. Both terms are referred to in definitions of *sink-hole* and *swallow-hole*, the first possibly, the latter definitively draining surface water or streams. However, the two categories are reconciled in a single synset in WNET. We thus decide not to use the terms with an origin in former Yugoslavia (*doline* and *ponor*), but instead use the English term *sink-hole*. This term seems somewhat more general and encompassing than the narrower *swallow-hole* which definitively implies the disappearance of a stream (although this requirement is attenuated in WNET). Since a uvala is a coalescence of dolines or sink-holes, it will generally be larger than the features composing it. Thus, we think the dimensions Mayhew (2004) gives for dolines (up to 1000 metres) as opposed to Whittow (2000; 10–100 metres) seem wildly exaggerated or exceptional. We consider sink-holes (besides poljes and uvalas) as the smallest of the three karst landforms.

Pit, cavity. WNET contains a synset *pit, cavity*. It is a hyponym of *hole, hollow* and (indirectly) *(natural) depression*. The definition is "a sizeable hole (usually in the ground)". The definition of *hole, hollow* reads "a depression hollowed out of solid matter". Neither *pit* nor *cavity* is featured in one of our reference works, except OED and Huggett (2007). Huggett (2007: 66) mentions "underground cavities, as in karst terrain" when writing about "cavity collapse". OED has several meanings for *pit*. Under the general heading "a hole in the ground, and related senses" it lists among others "[generally] a natural or man-made hole in the ground, usually a large or deep one". For *cavity* OED lists three meanings: "hollowness" (which is indicated as obsolete and rare), "a hollow place; a void or empty space within a solid body" and a naval meaning concerning the displacement of water by vessels. *Pit* is often used in geomorphometry literature which relates it to a six-fold curvature-based classification of DEMs. However, here we do not discuss the term in that particular meaning but want to investigate its semantic content. Basically, OED states that a pit is a hole in the ground, specifically: "usually a large or deep one". These measures of size most probably relate to human scales. This in turn makes a pit a small feature on the geographic scale. Further, *pit* implies at most that the feature at hand is relatively distinctive, i.e. not a shallow, hardly remarkable depression. Further than that the term does not imply anything – especially no properties or requirements regarding the sides or the floor, the material or the genesis of the feature. Thus we feel comfortable to use a *pit* category as a container for smaller (in the scale of several metres or few tens of metres), compact depressions. So we can categorise sink-holes as pits rather than basins which have other requirements or implications regarding their shape and size.

Kettle-hole. A synset *kettle hole, kettle* is contained in WNET as a hyponym of *hole, hollow*. It is there defined as "a hollow (typically filled by a lake) that results from the melting of a mass of ice trapped in glacial deposits". Whittow (2000) describes the formation of such a feature as follows: "It is formed when a body of ice becomes buried in an area of dead ice features as an ice-sheet slowly decays. As the buried ice mass finally decays, the surface sediments collapse to form a hollow which soon becomes water filled. As subsequent sediments gradually infill the depression it is rare that a kettle hole survives beyond any but the final glacial stage." The water-filled kettle-holes are called *kettle lakes* (Allaby and Allaby 1999). Of course, neither water-filled nor sediment-filled kettle-holes can be distinguished in a DEM; but kettle-holes need not be filled. According to Lapidus et al. (2003) kettle-holes range from 5 to 13 metres in diameter and have a depth of up to 43 metres (which renders them not detectable in coarse DEMs). However, these very specific numbers should probably be handled with care. They go on to state that "most kettles are of circular to elliptical shape, since melting ice blocks tend towards roundedness." Mayhew (2004) highlights kettle-holes in Mecklenburg, northern Germany. When many kettle-holes occur in conjunction with many mounds or kames, this type of terrain is called "kame and kettle moraine", "kettle moraine" (Lapidus et al. 2003) or "knob and kettle landscape" (see under "Hill-like features" in Section 3.4.1). Considering the usually limited extent of kettle-holes (possibly tens of metres in diameter) we decided to put them as a subcategory of the *pit* category – making them plausible siblings of sink-holes.

Deflation hollow/blowout, swale. *Deflation hollow* is not contained in any of our source works. However, they are mentioned by virtually all reference works we used. Whittow (2000) defines a deflation hollow as "a large-scale basin or depression formed by the action of the wind (deflation) in arid or semi-arid lands. (...)" According to him, with depth to the water table, the deflation hollow may also contain an oasis. Allaby and Allaby (1999) characterise deflation hollows as “enclosed depression[s] produced by wind erosion”. They may occur in hot deserts and in more temperate regions, “where a protective vegetational cover has been removed from a sand dune”. Blowouts seem to be small deflation hollows: A blowout is “a localized area of deflation, especially on a coastal sand dune” (Mayhew 2004) Allaby and Allaby (1999) equate the term to a “wind-eroded section of a sand dune (...)”. Huggett (2007: 299), by contrast, uses the terms *deflation hollow* and *blowout* as synonyms: “Deflation can scour out large or small depressions called deflation hollows or blowouts.” According to him, deflation hollows/blowouts vary strongly in size: from less than a metre deep and a few metres across, a few metres deep and diameters of hundreds of metres, and over 100 metres deep and over 100 kilometres wide. We include the category *deflation hollow, blowout* in our listing. We decided to put it as a subcategory of the *basin* category, since the term *basin* is used in some characterisations and the feature effectively seems to resemble a (rather shallow) basin. However, we doubt that the “localized area[s] of deflation” of Mayhew (2004) can be found in a coarse DEM and, especially, distinguished from other spurious depressions.

There is also a term *swale* in WNET described as “a low area (especially a marshy area between ridges)”. However, the definition of this item seems to be somewhat mixed up. Both, Kearey (2001) and OED feature two meanings of *swale*: firstly, “an area of low-lying, often marshy land” (Kearey 2001) or “a hollow, low place; esp[ecially in the] U.S., a moist or marshy depression in a tract of land, esp[ecially] in the midst of rolling prairie.” (OED) and secondly, “a shallow trough between storm ridges on a beach” or – as the above definition of OED continues – “Also (U.S.) a hollow between adjacent sand ridges”. Lapidus et al. (2003) define a swale as “a long, narrow depression between beach ridges”. Allaby and Allaby (1999) have (among others) a similar definition: “a long, narrow depression, approximately parallel to the shoreline, between two ridges on a beach”. Similarly to the depressions in between sand dunes and equally to sand ridges we estimate swales in the second meaning after Kearey (2001) as too small features to be detectable in coarse DEMs. We regard the first meaning as an amalgamate of landform and land cover and we therefore deem it not crucial in our context. Moreover, according to OED *swale* is of U.S. origin. Thus, *swale* is not contained in our landform taxonomy.

3.4.3 Topographic plains

Fig. 28: Tag cloud for the *topographic plains* listing.

Plains are contained as a category in SDTS, AFTT and SUMO-G. SDTS and AFTT concordantly define a plain as "a region of general uniform slope, comparatively level, and of considerable extent". SUMO-G: "A plain is a broad, flat or gently rolling area, usually low in elevation." Not surprisingly the collection of categories related to topographic plains is quite concise. The reason for this is that following a very strict definition of landforms (form of the land surface; no requirements regarding material, forming process etc.) there are not many different ways to subdivide (perfectly) level regions into different categories since their essence is the absence of any remarkable properties like surface undulations. Possible ways to nevertheless categorise such features may be (apart from material and forming process mentioned above) extent/size and spatial associations (e.g. *floodplain*), the latter being often tied to forming processes and/or material, however.

In SDTS included types of plain are *(archipelago) apron*, *coastal plain* and *outwash plain*. *Apron* is defined by Lapidus et al. (2003) as "a broadly extended deposit of unconsolidated material at the base of a mountain or in front of a glacier". The term is related to *outwash plain* and *sandur*. "Outwash plains are produced by the merging of a series of outwash fans or aprons" (Lapidus et al. 2003). *Sandur* is Icelandic and used to denote "a low-angle sheet of outwash material beyond the terminal moraine of a glacier" (ibid.). Kearey defines a sandur as "a large outwash plain created by the meltwater from an ice mass”. Whittow (2000) equates the two terms. Apart from the material (unconsolidated), the term *apron* (and maybe also *outwash plain/sandur*) seem not to denote very specific landform instances. They are therefore dropped from our taxonomy and subsumed in *topographic plain*.

The situation is similar with *coastal plain*. It is defined by SUMO-G as “the class of broad plain areas adjacent to a sea or ocean. A coastal plain includes a narrower shore area adjacent to a body of water.” The term is again very broad (although Whittow 2000 highlights a more concrete U.S. usage of the term) and therefore not deemed necessary in our taxonomy.

The term *flat* appears not widely known in the sense of the AFTT definition (“relatively level areas within regions of greater relief”). Kearey only portrays two very geologic usages of the term, while Lapidus et al. (2003) does not feature *flat* at all. Whittow (2000) offers four meanings for *flat*. The first is very general, “any smooth, even surface of low relief”. Other meanings refer to periodically exposed mudbanks (tidal flat), marshy pasture-land along a stream in an upland valley (valley flat) and horizontal parts of a mineral vein. Since tidal flats are not of interest (they are below high-water line) and other meanings of *flat* do not convey much information that is not already present in *plain*, we decide to drop the term from the taxonomy.

Salt pan is also missing in our taxonomy although they are featured in WNET and DIGEST. Of course salt pans are usually very level and would thus fit well into the category of plains. But the main distinction from plains is the fact that on its surface there are salt (and possibly gypsum) deposits which does not relate to a narrow landform concept and is thus not detectable using DEMs.

There are two categories in DIGEST and AFTT that are quite similar to salt pans. The first term, *sebkha* (or *sabkha*) is defined in DIGEST as “a natural depression in arid or semi-arid regions whose bed is covered with salt encrusted clayey soil”. However, literature suggests that *sebkha/sabkha* is a “broad plain or salt flat (...) containing evaporites (...)” (Kearey 2001) or “(...) the floor of a closed depression (...) characterized by the presence of salt deposits and the absence of vegetation. (...)” (Whittow 2000). Lapidus et al. (2003) and Allaby and Allayb (1999) describe *sebkhas/sabkhas* as planar features, not as depressions. However, we do not include *sebkhas/sabkhas* in our *topographic plain* category for the same reasons we excluded salt pans; also it is possibly quite a local term. The second term, *playa*, is contained in AFTT. Instances of this category are defined as “closed depressions in an arid or semi-arid region that are periodically inundated by surface runoff, or the salt flat within such a closed basin“. However, in our other sources we did not find hints at the first meaning suggested by AFTT. They all unambiguously describe playas as planar features. The term is also mentioned in Lapidus et al.'s (2003) definition of *sabkha*. These authors write explicitly that in the geological sense *sabkha* includes coastal and continental salt flats and that continental salt flats are called *playas* in North America. Indeed, the definitions for *playa* are quite similar to those for *sabkha*: "(...) a level or almost level area occupying the centre of an enclosed basin (...)" (Kearey 2001), "a flat dry barren plain at the bottom of a desert basin, underlain by silt, clay and evaporites. (...)" (Lapidus et al. 2003) or "a flat plain in an arid area found at the centre of an inland drainage basin (...)" (Mayhew 2004). The term *playa* is not included in our taxonomy for the same reasons we excluded salt pans and sabkhas.

Floodplain. Another term relating to plains (although nowhere contained explicitly as a subcategory) is *floodplain*, defined as "an area which is subject to periodic flooding" (SDTS). The definition by OSHO is more specific: "the relatively flat part of the valley bordering a river resulting from alluvium deposited by a river in times of flood." AFTT (as SDTS) does not confine the term to land along rivers but uses it also to denote "tidal area that is covered by water during a flood". However, we stick with the European (OSHO) interpretation that is also followed by Lapidus et al. (2003) and Whittow (2000). This definition relates floodplains very much to valley floors. Prerequisites to talk of a floodplain are that the flat valley floor has to be of a certain width and that a river flows through it and that the plain results from alluvium deposits as OSHO suggests. Both *floodplain* and *valley floor* are boundary cases and difficult to place in our landform taxonomy, since they can equally well or maybe even better be regarded landform elements. Firstly, they are often perceived as *parts* of the landform *valley*; secondly, they usually have a limited extent. We decide not to feature either in the *topographic plain* category.

Pediment, bajada and piedmont. Pediments do not appear in any of the reference works but we mentioned them before in the section on monadnocks and inselbergs. A pediment is characterised as a "surface of low relief, partly covered by a skin of rock debris, that is concave-upward (...)" (Allaby and Allaby 1999) and has low slope angles, "normally less than 5°" (ibid.) or less than 7° (Mayhew 2004). Where no overlaying alluvium is present, the bedrock is exposed (Lapidus et al. 2003). Pediments have varying areas "from tens of square metres to hundreds of square kilometres" (Mayhew 2004). Ahnert (1998: 223) goes more into detail specifying that a pediment joins a steeper backslope of 20° or more by a sharp break of slope at its upper boundary where it generally has an angle of 7° or less. Downslope it is flatter and hence concave in profile. Pediments are associated with the "base of a mountain zone or scarp" (Allaby and Allaby 1999), the "foot of a mountain" (Mayhew 2004) or with a "mountain front" (Lapidus et al. 2003). Pediments can be mistaken for bajadas/bahadas or vice versa. The latter is not an erosion surface but formed by deposition (Lapidus et al. 2003, Whittow 2000). Bajadas/bahadas can be closely associated (downslope neighbour) with pediments. According to Whittow (2000) the term *piedmont* can be used to denote "(…) the gentle slope leading down from the steep mountain slopes to the plains and including both the pediment and the accumulation of colluvial and alluvial material which forms a low-angle slope beyond the pediment (bahada)". For slopes of slightly more than 10° that resemble pediments, Whittow (2000) suggests the term *footslope*. We decided to include the common term *pediment* as a subcategory to *topographic plain* in our landform taxonomy.

Pediplain. *Peneplain* and *pediplain* are well-known terms in geomorphology that allude to plains but are not contained in any of the source works used in our study. However, it is unclear how relevant these features are to us. The question is if and where they occur (the definitions are disputed) and whether they can be sensibly expected to be extracted from DEMs.

The occurrence of pediments is described especially in arid and semi-arid regions (Allaby and Allaby 1999, Mayhew 2004). However, according to some references put forward by Ahnert (1998: 223) they are also found in the arid tropics, in western Argentina, in Central Asia and in the Arctic periglacial climate. Ahnert (1998: 223f.) describes the formation of pediments and finally pediplains using the example of the Great Basin in USA. There are a number of uplifted crustal blocks, forming small mountain ranges with intervening downfaulted, sediment-filled basins. Pediments have developed at the margins of the blocks. Streams from the mountains undercut the slopes of mountain spurs at their valley exits by what is termed lateral planation. This leads to a retreat of the mountain spurs and to the development of a continuous pediment. The mountain edges retreat further until finally two pediments may get in contact with each other from opposing sides of a divide. This splits the range into individual inselbergs. Then "(…) the pediments reach the divide in broad front so that only a few inselbergs remain; the result is a pediplain sloping at low angle from both sides of the divide to the neighbouring basins. Consequently, pediplains are also described as "coalesced pediments" (Allaby and Allaby 1999). They are "extensive plains (…) showing gently concave or straight-slope profiles and terminated abruptly by uplands" (ibid.). Similarly to *pediment* we decided to include *pediplain* as a subcategory of *topographic plain*.

Peneplain. Opposed to pediplains, the peneplain (literally: "almost a plain"; an erosion surface, as well) is thought to be the product of down-wearing and the end-product of the Davis(ian) cycle (Allaby and Allaby 1999) or "the wearing away of the entire landscape" (Mayhew 2004). The peneplain is described as "an extensive area of low relief, dominated by convex-up ('bulging') hillslopes mantled by continuous regolith (…)". Monadnocks may occur (Allaby and Allaby 1999), Ahnert (1998) calls the individual hills "inselbergs". But according to Mayhew (2004), most existing peneplains are old and have been rejuvenated through uplifting and dissected again. "Peneplanation is the wearing away of the entire landscape, so that the planation surface evolves over all sections at all times, whereas in pediplanation the scarps are subject to progressive retreat." (ibid.)

Lapidus et al. (2003) see the peneplain rather as a concept: "a hypothetical surface to which landscape features are reduced through long-continued mass wasting, stream erosion and sheet wash (peneplanation)." This view may be linked with the advent of the concept of peneplains as the "end-product of the normal cycle of erosion, as defined by W. M. Davis in 1889 (…)" (Whittow 2000). Ahnert (1998: 221) highlights that "it was not Davis's primary intent to describe the development of an actual landscape but to order the morphological developmental stages into a model." However, there has been considerable criticism of Davis's theoretical concept (Whittow 2000, Ahnert 1998: 221f.). While Ahnert acknowledges that some peneplains (e.g. in Cornwall, UK) may have been formed by marine abrasion and subsequent uplift he denies that this theory can explain most peneplains. Ahnert (1998: 225) treats pediplains as subtypes of peneplains (this also explains his usage of the term *inselberg* (instead of *monadnock*) with *peneplain*): "The difference in appearance between pediplains and peneplains formed by other processes is small, particularly in the late phases of pediplanation. L. C. King (1953) suggested that many peneplains result from the combining of pediments following pediplanation." We include the *peneplain* category in our landform taxonomy as a subcategory to *topographic plain*.

Delta, alluvial fan. *Delta* is contained in WNET, SDTS, AFTT and SUMO-G. It is defined as "a low triangular area where a river divides before entering a larger body of water"

(WNET), as “flat plains formed by alluvial deposits at the mouth of a stream” (AFTT) or as “a Delta is a LandForm composed of silt or other alluvium, deposited at or near the mouth of a river or stream as it enters a body of relatively static water. Typically a delta is flat and fan-shaped.” (SUMO-G). Thus the *delta* category is indeed often related to plains or planar features. Differing from *floodplain* and *valley floor* (which were excluded from the category *topographic plain*), instances of the *delta* category are not so much perceived to be part of a larger landform, i.e. to be a landform element. We thus put the *delta* category into the *topographic plain* category although it probably lacks some characteristics; for instance, there are certainly deltas which do not have a particularly large extent. As such, the *delta* category is also very close to categories concerning “forms of coastlands or arrangements of water and land” which were excluded from the analysis (see Section 3.2.8). In practice, working with a DEM alone it is probably impossible to specifically delineate a delta as these features often blend in with floodplains or valley floors in DEM-based morphological assessment.

In SDTS and AFTT deltas are related to (alluvial) fans. These in turn are defined as “a gently sloping fan shaped feature usually found near the lower termination of a canyon” (DIGEST) and as “fan-shaped deposits of alluvium (...)” (AFTT). Although these features can adopt a certain slope gradient, we decide to put them in the *topographic plain* category for the sake of simplicity.

Generally, we must state about the subcategories of *topographic plain* that many of these almost certainly cannot be distinguished from a DEM alone. It may well be, that some additional, higher-level reasoning (e.g. regarding landscape context, active processes, material properties) is required to recognise such features. Also, it has been highlighted above, that some of the forms and the linked processes are still subject to scientific debate. Generally, we hold the opinion, that the extraction of instances of the superordinate *topographic plain* category may both be the maximum which can be achieved and represent a sufficient level of information for most potential applications.

3.4.4 Landform elements

Appendix C also contains a listing of landform-related terms or categories which we would tentatively assign to the class of landform elements rather than landforms. Examples are *summit/peak*, *pass/gap/saddle* and *slope*.

Slope is a very typical landform element in our opinion, since in order to 'build' instances of the more complex category of landforms (which is tentatively subdivided into *topographic plains*, *depressions* and *eminences*) we need sloping elements (at least for *depressions* and *eminences*). Conversely, sloping elements can be regarded neither as depressed nor as elevated, they are simply *inclined* and judgment of their position or vertical tendency solely depends upon the relative positions of the observer and the feature. Many of the categories in the tentative landform element listing echo the six-fold classification into morphometric features (e.g. Wood 1996; however, the category of ridges has been described in Section 3.4.1 to denote both a self-contained landform as well as a landform element which is often part of e.g. mountains). This further shows that there is indeed a valid point in this classification approach. The classification is further subdivided by gradual variation and/or by material/process properties (as in the differentiation of sloping elements into simple slopes, terraces, scree or talus slopes, escarpments, bluffs and cliffs). Some of these, however, are not genuinely new. For example, Felicísimo (2001) has suggested an expansion of the morphometric feature classification scheme based on gradient, specifically – according to Bolongaro-Crevenna et al. (2005) – Felicísimo (1999) proposed the inclusion of categories like *cliff* and *ramp*.

3.4.5 Landform taxonomy and overview of characteristics

Fig. 29 shows the full landform taxonomy as it is also textually described in Sections 3.4.1 through 3.4.3. One has to keep in mind that this taxonomy left out many landform candidates for reasons of simplicity and reduced redundancy. We think that it can serve well as an initial framework to both ontological engineering in the domain of geomorphology and to devising possibly all-encompassing landform classification approaches.

It is readily visible that the taxonomy of topographic eminences is deepest whereas the taxonomy of topographic plains is the shallowest. The latter is not surprising since there can only be a limited amount of variation in the characteristics of basically planar features. The *topographic eminence* category is relatively complex mainly because of the inclusion of the *dune* and *moraine* categories. These two categories – while (since) not morphologically defined but having strongly material- and process-dependent definitions – unite many features having various forms.

As for the categories *polje*, *uvala*, *monadnock* and *inselberg* it was not deemed sensible to put them into one single superordinate category. Thus they are each linked to two potential superordinate categories. We are also convinced that they are not as commonly known as most of the other landform categories.

Additionally to what has been textually described in some detail in Sections 3.4.1 through 3.4.3, Figs. 30 and 31 show basic form characteristics of the subordinate categories of *topographic eminence* and *topographic depression*. The “clouds” in the background of the figures are an attempt to qualify the (necessarily fuzzy) potential parameter space a landform appropriates. In some instances the fuzziness is depicted rather conservatively in order to avoid cluttering the figure. Fig. 30 (both left and right) features lines of proportions (1:1 and 1:10) of vertical versus horizontal extent. These are also given explicitly in Section 3.4.1 which states that buttes are higher than wide and that the length of a barchan is about ten times larger than its height.

Note that for topographic depressions the shorter horizontal dimension (if the feature is elongate) is depicted in Fig. 31 (rather than the length as in Fig. 30). Lengths of elongate topographic depressions are likely to vary as well among categories (e.g. it is conceivable that flat-floored valleys are on average longer than gorges); however, in these cases length is much less informative than width which is often considered, for example, in the depth-width-ratio (which can be approximately extracted from Fig. 31). The categories *deflation hollow, blowout* and, especially, *basin* are rather diverse regarding their extents and depths. Thus the potential parameter space of these categories is depicted using a dotted outline instead of a cloud so as not to further confuse the figure’s backdrop.

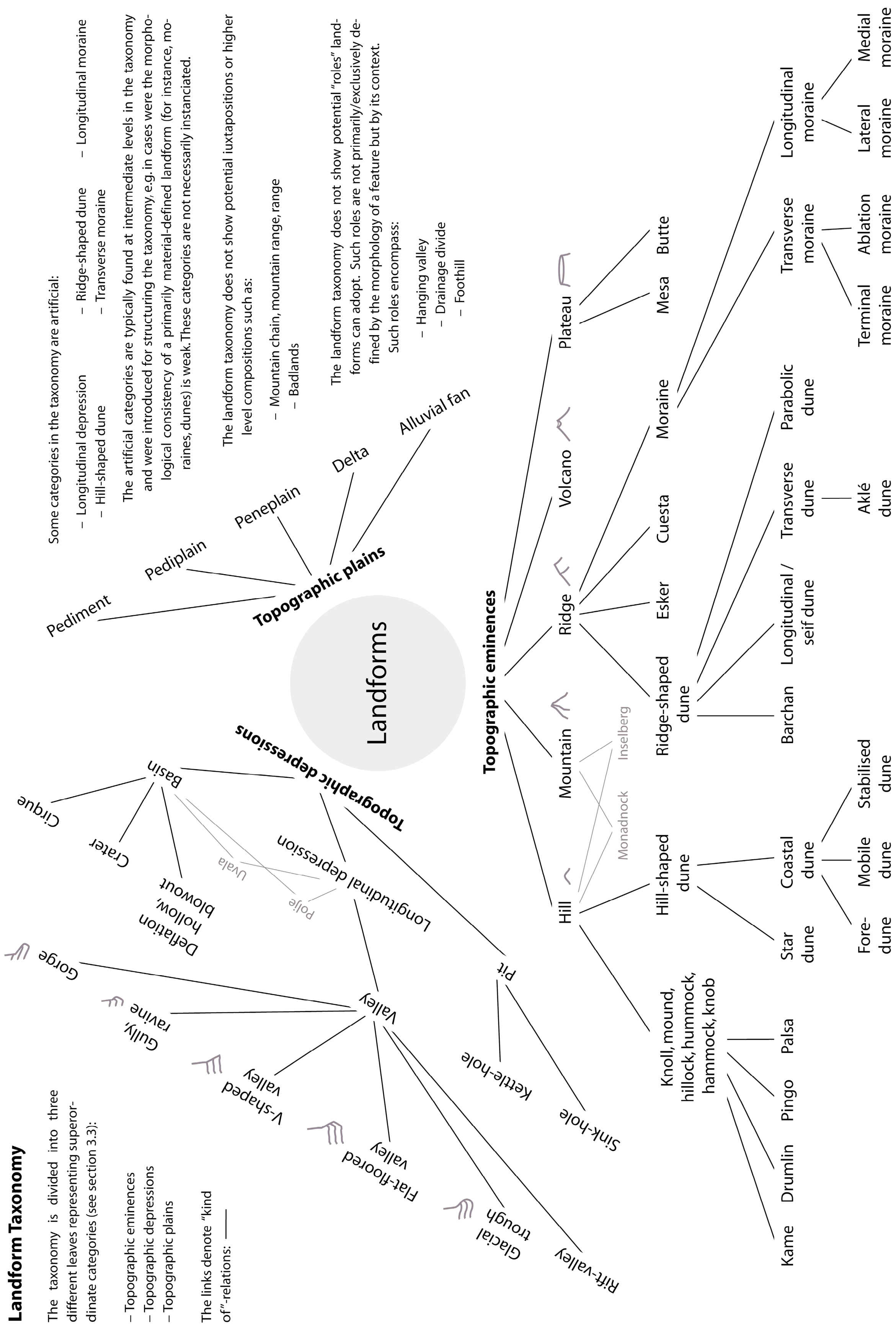


Fig. 29: The landform taxonomy.

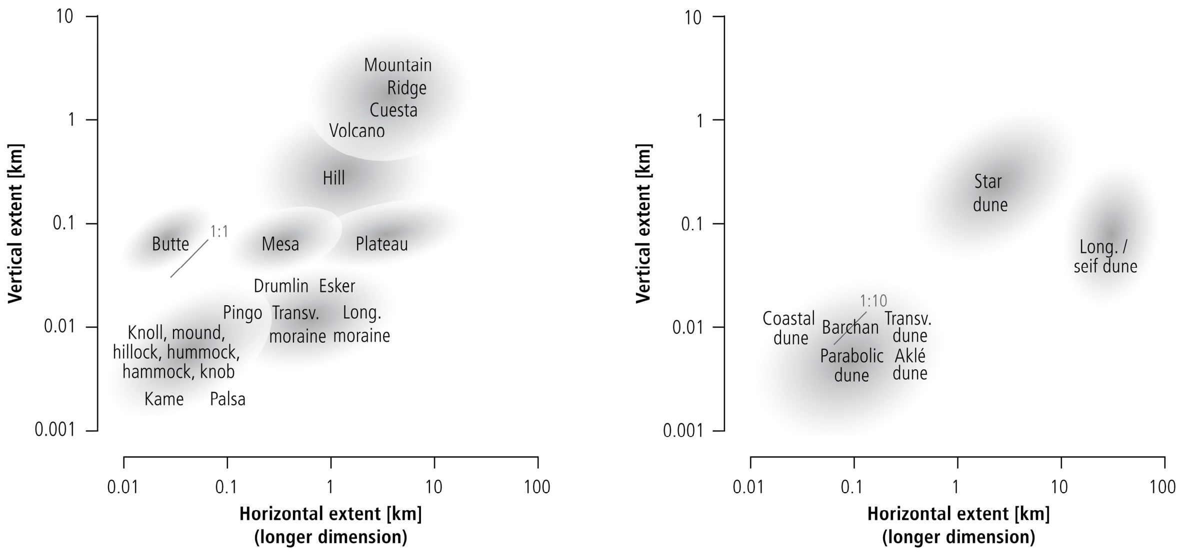


Fig. 30: Dimensions of *topographic eminences.*

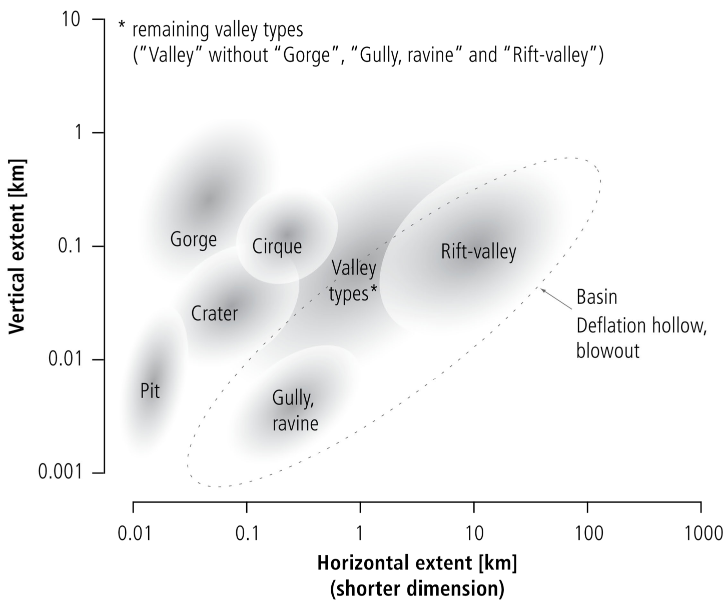


Fig. 31: Dimensions of *topographic depressions.*

Fig. 32 depicts process realms typically associated with subordinate categories of *topographic eminence* and *topographic depression*. Of course, the attribution of processes to landforms is not always straightforward. Fig. 32 tries to highlight what is considered to be the *main* process acting in the formation and coining of each landform category listed. It thus also allows grouping the landform categories according to their associated processes. Often, these groupings will also be spatially informative, in the sense that we would expect co-occurrence of the grouped landforms where their respective process (combination) is active – provided other requirements (e.g. presence of certain materials, orders of magnitude of processes) are either also fulfilled or inexistent (i.e. the mere process is sufficient to lead to the formation of a landform without additional requirements).

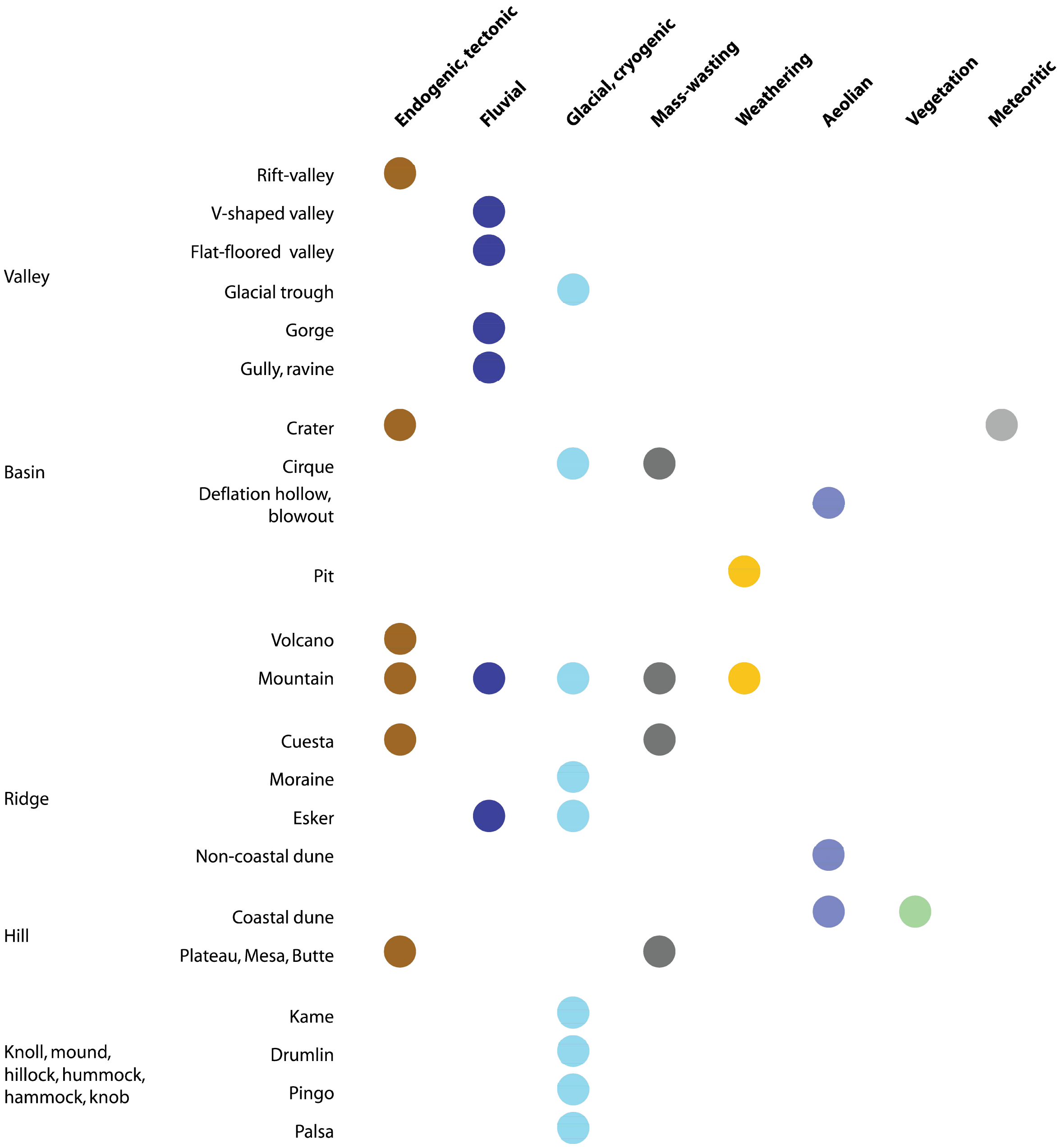


Fig. 32: Typical process realms associated with *topographic depressions* and *eminences*.

3.5 Applications of geomorphologic knowledge

This section briefly outlines the structure of the subsequent, second part of the thesis which consists of the Chapters 4 to 6. After this chapter which dealt with the ontology of landforms, the second part of the thesis will present applications of the obtained insights. Specifically, it deals with the application of geomorphologic domain knowledge to the design and implementation of what are termed top-down extraction and characterisation algorithms for landforms. As already mentioned in Section 2.4, the research of algorithms and applications described in Chapters 4 to 6 deals with valley-like topographic depressions and their parts (such as valley floor and valley side slopes). Besides developing algorithms to extract and characterise valley-related landforms we will detail an application of one extraction algorithm in the field of geomorphology and we will compare findings of algorithms to what could be termed Naïve Geography knowledge.

The second part of the thesis is composed of three individual case studies. For the sake of their different foci and also discipline of application they are presented separately, although they are closely related methodologically with respect to the underlying assumptions and algorithms:

Chapter 4: The first case study deals with the foundations and the actual implementation of a top-down algorithm to crisply extract valley floor from a DEM. The extracted valley floor is compared to valley delimitations gained from Naïve Geography knowledge or sources (mostly textual) and to the morphometric feature classification (Wood 1996).

Chapter 5: The second case study describes application and interpretation of the valley floor delineation in a specific geomorphological research context. The study is centred on geomorphological interpretation of and further investigations into the sediment deposits forming valley infills at the scale of the European Alpine mountain-belt.

Chapter 6: The third case study extends the valley floor extraction algorithm by a method to characterise valley side slopes. It argues that, combined, the valley sides characterisation and the valley floor extraction characterise the landform *valley* through a measure of “valleyness” of a location. The case study discusses the quality and investigates the validity of this valleyness characterisation employing a human subject experiment with photographs.

The three case studies are presented sequentially but roughly in a parallel pattern. Each section is structured more or less as one would expect from an individual scientific publication. So, each section dealing with a case study presents the scientific background and methodology relevant to that study, but avoids repetition of the comprehensive literature review in Chapter 2 as well as the literature reviews in preceding case studies.

"The next day went well. With Oberlin through the valley on horseback; broad mountain slopes funneling down from great heights into a narrow winding valley leading this way and that to the upper elevations, great boulder fields fanning out at the base, not much woodland, but everything a gray somber cast, a view to the west into the countryside and onto the mountain range running straight from north to south, the peaks looming huge, solemn, or mute and motionless, like a twilit dream. Enormous masses of light sometimes surging out of the valleys like a golden torrent, then clouds again, heaped around the highest peaks and then climbing down the forests into the valley or darting up and down in the sunbeams like silvery fluttering ghosts; no noise, no movement, no birds, nothing but the sighing of the wind, now near, now far."

from *Lenz* by Georg Büchner

4 Devising and testing a valley floor extraction algorithm

4.1 Introduction[2]

In what follows a case study using techniques based on both popular notions of a specific valley in Switzerland (what we term Naïve Geography knowledge) and a top-down method developed to extract valley floors from a DEM will be described.

We firstly set out a range of related work on the extraction and definition of landforms and landform elements pertaining to valleys and their features and list some definitions of the landforms *valley* and *valley floor*. Subsequently we detail simple methods to extract approximations to a specific valley mostly from natural language descriptions, before we introduce our DEM-based algorithm for the delineation of valley floors. The algorithm results are related to the Naïve Geography depictions and compared to an alternative geo-morphometric characterisation.

4.2 Background and research gaps

Researchers from several fields have investigated methods to extract valleys or features pertaining to valleys from digital representations.

[2] Chapter 4 is largely based on Straumann and Purves (2008).

Tribe (1991) aimed to automatically recognise valley heads from DEMs by application of a region growing algorithm on seed cells near the upper end of simulated drainage branches she refers to as "valleys" or "valley lines". The region growing was determined by slope gradient and concavity in plan. In a follow-up paper, Tribe (1992) again reviewed shortcomings of existing "valley and drainage network recognition" methods. Most of the reviewed methods seem to yield one pixel wide "valleys". A new method improving upon the methodology by Carroll (1983) was proposed, including a threshold slope in order to eliminate insignificant depressions and including a larger user-defined neighbourhood in order to reduce network discontinuities in wide, flat-floored valleys.

Miliaresis and Argialas (1999) also applied a gradient-dependent region growing algorithm for their delineation of mountains, piedmont slopes and basins from GTOPO30. They used pixels with higher-than-mean flow accumulation as seed cells for basins and, with upslope flow direction, for mountains. However, "the seeds for basins did not give the impression of a network" (1999: 720), since basins had gradients less than 2° and aspect/flow direction was undefined. "Thus, the high order valley lines remained undetected" (ibid.). However, the resulting segmentation seems to have overcome this limitation. It was favourably compared to a physiographic map of the region. The extraction of mountain objects but not of basins and slopes was then successfully tested in two additional regions and later re-used in another study (Miliaresis and Argialas 2002) which aimed at further describing the extracted mountain-objects with additional topographic attributes (cf. also Miliaresis 2006).

Chorowicz et al. (1992) proposed a method for the extraction of drainage networks of areal features. The method seeks to combine a threshold-based "profile scan" and the "hydrological flow routing" method to overcome the problem of hydrological flow routing yielding one-pixel wide channel networks.

Sagar et al. (2003) studied the extraction of what they term ridge and valley connectivity networks (RCN and VCN). The authors used operations from mathematical morphology (multi-scale opening and closing, erosion and dilation of the DEM) to extract these networks. While the results for the RCN look relatively sensible, the method seems to have problems with flat-floored valleys where, for smaller neighbourhoods, the concave areas where the valley floor joins the valley sides seem to be extracted rather than the valley axes.

A very different, contour-based approach to hill and valley extraction was proposed by Cronin (2000). One problem of contour-based delineation is the ambiguity of open contours. This is resolved by arbitrarily choosing the smaller area on either side of the open contour as the interior of the contour line. The extraction method is exemplified at four sites. However, three of them feature hills and valleys of approximately half the size of the study area and the fourth example seems to suggest that the presented algorithm tends to derive hills and valleys of a size that is controlled by the map extent and scale.

As already detailed in Section 2.3.4, several authors (e.g. Wood 1996, Fisher et al. 2004) have implemented curvature-based methods on a multi-scale basis – operationalised as varying window sizes for curvature calculation. However, the study by Fisher et al. (2004) focused on mountains or convexities rather than valleys. While the multi-scale nature of such approaches is better able to portray landscapes with their inherent multi-scale properties, the problem of choosing an appropriate window size (or range of sizes) for characterisation is unsolved. Gallant and Dowling (2003) applied an, in some respects, similar method to the fuzzy characterisation of valley floors. However, instead of multi-scale curvatures they based their method on slope gradient (representing the flatness of such features) and elevation percentiles (representing lowness with respect to the surroundings).

In identifying the borders of any region, or to be more specific to the case at hand, landform, it is important to consider the ontological nature of the region and its borders. Landforms are generally classical examples of fiat objects, i.e. they are defined by human perception and do not have a physically unambiguous expression on the earth's surface because they are vague (see Section 2.1). Thus, the area which is unambiguously a valley cannot, by definition, be defined. Recent work has sought to define the boundaries of similarly vague fiat regions for so-called vernacular regions, regions which are used in common parlance but have no official or administrative boundary. Examples of such regions include *downtown* or *the American Mid-West*. Montello et al. (2003) investigated this problem by asking residents of Santa Barbara to sketch the boundaries of *downtown* on a map. More recently, Jones et al. (2008) searched for place names co-occurring with vernacular regions, and used density surfaces to estimate the borders of the fiat regions. Both of these sets of techniques used human perception of the boundaries, or locations found inside a region, to delineate a spatial extent for vernacular regions.

As has been noted before (Section 2.4), in general, work on the delineation of landforms and landform elements has focused on the latter and often on bottom-up methods (i.e. without very much semantic consideration). When approaches to landform rather than landform element classification were put forward, they were usually centred on topographic eminences.

Therefore, in this case study we will address the issue of the extraction of valley (floors) from two perspectives. On the one hand a perspective from Naïve Geography is adopted using among others everyday language descriptions and toponyms in maps. On the other hand a top-down geomorphometric approach is devised, the results of which are contrasted with the Naïve Geography descriptions. Furthermore, we will compare the geomorphometric characterisation to the classification of topography into six geomorphometric classes (Wood 1996).

4.3 Methodology

4.3.1 Study area and data

Our study area comprises Switzerland and adjacent regions contained in its buffered bounding box (Fig. 35 on page 132). Thus the study area covers a considerable extent of the European Alps. For the detailed analyses (e.g. comparisons with Naïve Geography sources and another geomorphometric characterisation), the case study partly focuses on the Gürbe valley and adjacent Aare valley near the centre of the canton of Berne in western Switzerland (cf. box in Fig. 35).

As a data source we used the hole-filled Shuttle Radar Topography Mission (SRTM) DEM (version 3) at 3 arcseconds resolution (roughly 90 metres) obtained from Jarvis et al. (2006). The DEM was projected into the Swiss national projection system and resampled to 100 metres resolution.

On an important note, it has been shown through comparison with independently derived elevation data that the C-band interferometric synthetic aperture radar (InSAR) methodology of SRTM produces larger elevation errors in areas of greater topographic roughness as well as an increasing bias in elevation error with denser vegetation or increasing presence of built structures (Carabajal and Harding 2005, 2006; Shortridge 2006, Hofton et al. 2006). But, firstly, our research is interested in relatively large scale landforms (valley floors and valleys) and, secondly, the method implemented in this case study relies on relative elevation differences of raster cells and is less dependent upon absolute elevation accuracy. These two factors to some degree alleviate the effect of potential SRTM errors.

Thus it was decided not to try and correct, for example, potential vegetation-induced errors.

4.3.2 Valley floor delineation

Definitions for valleys and valley floors. As can be seen in Chapter 3 of this thesis, there is a range of definitions for the term *valley* in the literature. Here we re-list three typical examples:

1. a low area more or less enclosed by hills (OSHO);
2. a long, narrow depression in the Earth's surface, usually with a fairly regular downslope (SDTS); and
3. (a) any low-lying land bordered by higher ground; especially an elongate, relatively large, gently sloping depression of the Earth's surface, commonly situated between two mountains or between ranges of hills or mountains, and often containing a stream with an outlet. It is usually developed by stream erosion, but may be formed by faulting. (b) a broad area of generally flat land extending inland for a considerable distance, drained or watered by a large river and its tributaries; a river basin. Example: the Mississippi Valley (Bates and Jackson 1990).

As opposed to the extremely general (and thus rather less useful) notion of (1), (2) specifies the shape of the valley explicitly as "long" and "narrow". Additionally, a valley "usually" has a "fairly regular downslope". (3) begins similarly to (2) but then gives some detail, for example, the gentle slope and the presence of streams. Consequently, in Section 3.4.2 we adopted the view that valleys are elongate depressions of the earth's surface, often with a stream or river and a usually gentle, fairly regular downslope. Regarding their cross-sections valley can differ considerably as was explained in the respective paragraphs of Section 3.4.2 and illustrated in Fig. 29 (page 118).

The terms *valley floor* or *valley bottom* appear infrequently in reference literature and did not come up at all in the ontological investigations in Chapter 3 (only DIGEST contains a related category *valley bottom line* denoting thalwegs). Here, we thus turn to more specialised reference works. The McGraw-Hill Dictionary of Earth Science (2003) characterises a valley floor as "the broad, flat bottom of a valley" and says it is "also known as valley bottom; valley plain". Bates and Jackson (1990) define it as "the comparatively broad, flat bottom of a valley; (...)" and refer to *flood plain* as synonym. However, *flood plain* has the implication and affordance of being occasionally inundated by a river (and thus implies that a valley floor must, in contrast to the above, contain a river). In conclusion we can say that a valley floor is a relatively broad, flat region within a valley and will thus inherit the characteristics of valleys as mentioned above. This can be illustrated with the assertion that valleys are low areas relative to their surroundings. Since valley floor is defined to be the lowest part of a valley, it, too, is certainly lower than its surroundings. Two other characteristics of valleys (being gently sloping and often containing a water course) even refer more to the valley floor than to any other part of a valley.

Operationalisation. Maxwell's (1870) work was chosen as a starting point for developing our method to extract valleys from a DEM, the eventual aim of this work. Maxwell's dales equal drainage basins; these effectively enclose valleys. The enclosing relation of a drainage basin and valleys may be one-to-one in small headwater drainage basins containing a single water course reach and thus also a single valley (if the other defining criteria for a valley are met). However, the one-to-one relationship is of course not at all the case for drainage basins of higher hydrological order. These may contain several water course reaches and several valleys or valley stretches. Thus, in order to narrow down the search area for valleys, we clip the drainage basins of a certain Shreve order (Huggett 2007: 191p) with contributing drainage basins of lower orders (cf. also Demoulin et al. 2007). Shreve order assigns headwater streams an order of 1 and sums up the orders wherever streams merge (Fig. 33).

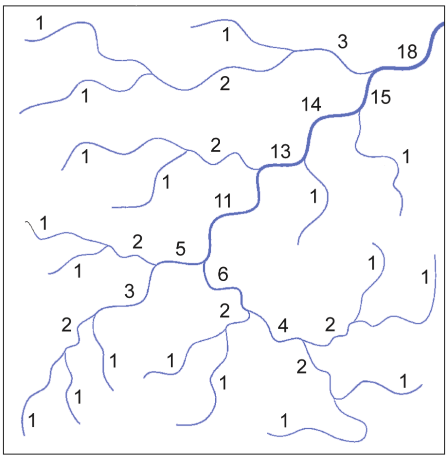


Fig. 33: A Shreve-ordered drainage network (adapted from Huggett 2007: 191).

A *drainage sub-basin* is thus defined as a core area more closely related to one valley than the original drainage basin spanning over several valleys (Fig. 34).

Starting from the definitions listed in the previous section we assumed that streams or thalwegs could well serve as conceptual cores of valleys and their floors; cf. also Deng (2007: 412) who classified summits and stream channels as bona fide objects which can give "prototypical objects (eg, peak areas and valley bottoms) a conceptual core". Hence, valley floors can be described as relatively flat areas bordering thalwegs. Thus, valley floors can be extracted by imposing a gradient threshold on a region growing procedure seeded by thalweg/stream cells. In accordance with the assertions on the relations of drainage (sub-)basins and valleys we also imposed a drainage sub-basin constraint – region growing was allowed to only occur within, and not across, sub-basins.

Algorithm. The DEM was filled to remove artificial sinks and D8 flow directions (Jenson and Domingue 1988) and a flow accumulation grid calculated. Through imposing a channel initiation threshold of ≥ 500 cells (equates to 5 km^2) a stream network and its Shreve ordering was derived, with pourpoints being created where streams of differing orders merged. Thus, the stream network was segmented along general flow direction. Subsequently, drainage basins of order x were clipped by all drainage basins of order $y < x$, i.e. each segment of a river between two tributaries has its own drainage sub-basin (Fig. 34). A raster dataset was computed storing for each drainage sub-basin its hydrological order and an ID unique amongst the sub-basins of that order.

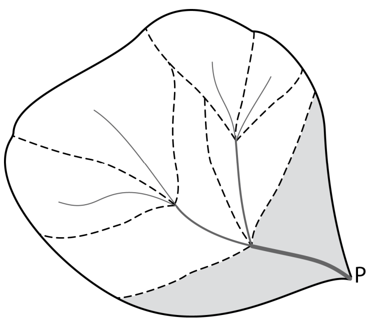


Fig. 34: Clipping of drainage basins. Solid outline represents original drainage basin of point P, dashed outlines represent several drainage sub-basins pertaining to different streams (grey lines). The drainage sub-basin of point *P* is represented by the grey area.

Using this raster and a raster of the streams a region growing procedure employing stream cells as seeds was carried out. Growing was allowed to occur only within an individual drainage sub-basin. A raster cell i was classified as pertaining to the valley floor, when at least one of its neighbours was a seed cell or a grown valley floor cell and at least one of the following conditions concerning the elevations of cell *i* and the seed cell was met:

$$\text{Cardinal neighbours: } \tan(\gamma_{crit}) \cdot \lambda \geq elev_i - elev_{seed} \geq 0 \quad (9)$$

$$\text{Diagonal neighbours: } \tan(\gamma_{crit}) \cdot \sqrt{2}\lambda \geq elev_i - elev_{seed} \geq 0 \quad (10)$$

where γ_{crit}: gradient threshold [°], λ: cell size [m], $elev_i$ and $elev_{seed}$: elevation [m] of cell *i* and seed cell, respectively.

This procedure ensures that valley floors are contiguous and that only those areas which can be reached from the thalweg with a low slope are delineated as belonging to the valley floor, thus matching the definitions for valley floors in the beginning of this section. Note that the methodology does not employ a traditional slope gradient computation algorithm (see Section 2.2) but uses a very simple notion of cell-to-cell gradient. This diminishes the "footprint" of the method drastically (20,000 m^2 versus 90,000 m^2 for a 3 by 3 cells computation). This may be attractive due to the resolution of SRTM which is quite coarse already anyway. Still, also with this algorithm resolution sensitivity applies, however, potentially to a lesser degree.

Region growing was run iteratively until no new valley floor cells were detected. We tested a range of gradient thresholds (γ_{crit}) from 0.25° to 3° and subjected the results to qualitative visual examination. Overlaying the delineated valley floor areas onto terrain parameters such as a hillshaded relief and a gradient raster we found the best accordance of the delineation with our subjective judgement for a threshold value of 1.5° gradient. This value was used in the following evaluation.

4.3.3 Exploiting Naïve Geography sources

For Naïve Geography delineations of the Gürbe valley we primarily investigated natural language descriptions from internet sources provided by both the general public and the tourism organisation in the area. These descriptions thus deliberately do not portray a specialist or geoscientific view of the valley or of valleys in general.

The general public's view was operationalised using Wikipedia. Although the community model ('crowd-sourcing') of this online reference work has its limitations, Wikipedia is very commonly referred to. Wikipedia (s.a.) is split into language groups, the encyclopaedic coverage and, of course, regional focus of the language groups differing significantly. There were 2,150,000 English articles vs. 690,000 German articles as of January 7th, 2008.

We referred to the tourism association of the Gürbe valley (Verkehrsverband Region Gürbetal s.a.) for the tourism perspective. A snapshot of the website was obtained as of February 2nd, 2007 from the Internet Archive (s.a.).

In order to gain additional clues on the extent of the Gürbe valley and some other topographic features mentioned by Wikipedia, toponyms in Swiss topographic maps were analysed, similarly to Fisher et al. (2004). For this purpose three scales of Swiss maps, 1:25,000, 1:50,000 and 1:100,000, were employed.

For comparison with DEM-based methods, and due to the limited number of points, convex hulls were derived for toponym label locations associated with the Gürbe valley (from the tourism association), whilst region boundaries (from Wikipedia) were used *as is*.

4.3.4 Morphometric feature classification

The valley floor delineation was also compared to the geomorphometric characterisation which classifies each location into one of the six morphometric classes *pit*, *channel*, *pass*, *ridge*, *peak* and *planar*. Following the methodology of Wood (1996) for multi-scale geomorphometric characterisation we used the software LandSerf (s.a.) to compute classifications over various window size ranges for implicit surface fitting. We chose to adopt the thresholds of 1.5° and 0.1 for gradient and curvature, respectively. 1.5° simply equates to the gradient threshold that was used for the valley floor delineation. For curvature a more relaxed threshold of 0.5 has been tested. This, however, resulted in an explosion of the occurrence of planar features (85% of the whole area at a small window size range) and the discontinuation of that analysis.

4.4 Results and discussion

Fig. 35 shows delineated valley floors in Switzerland and bordering regions. Note the floors of the broader alpine valleys, the conspicuous Rhine valley near the border of Switzerland, Liechtenstein and Austria in the upper right corner and the Rhône valley in southwestern Switzerland. Note also the floor of the Rhine Graben marking the border of France and Germany. While the extents of valley floors in the Swiss Prealps and in the lowland seem relatively sensible, the delineation may be problematic in France near the western border of the study area. There an obviously less accentuated topography leads to large regions being classified as valley floor.

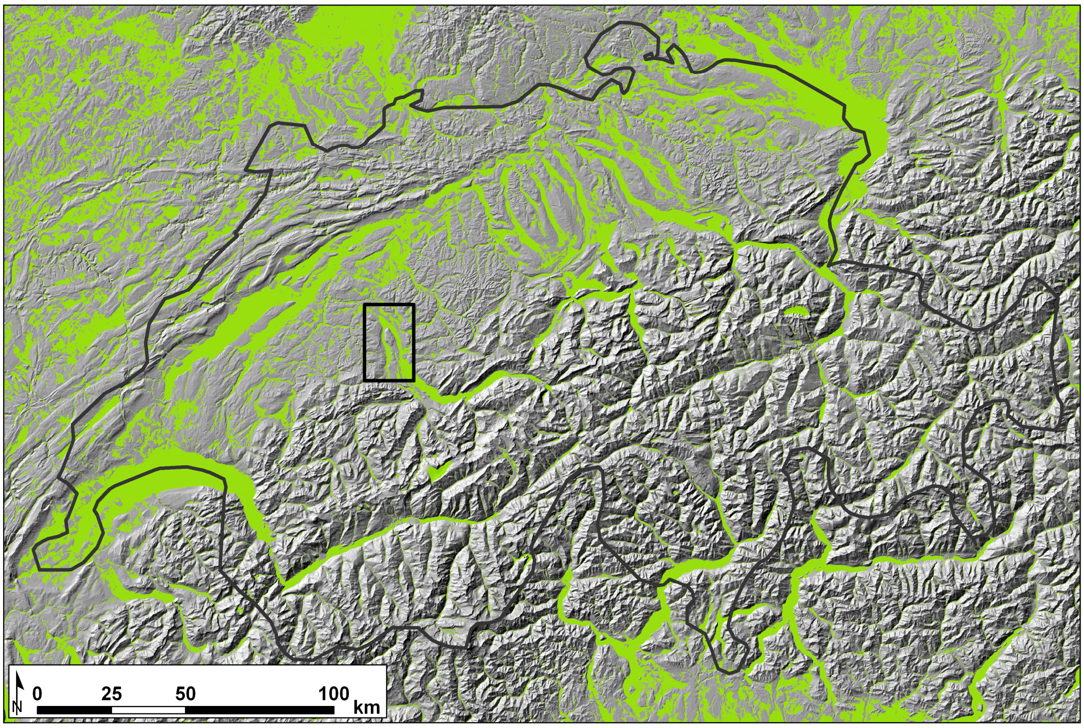


Fig. 35: Delineation of valley floors (light green areas) using 1.5° threshold in the area of Switzerland (border in black). The black frame denotes the region of the Gürbe (and Aare) valley subsequently analysed in detail.

In the remainder of this section the extent of the delineated valley floor in the Gürbe valley (Fig. 35) will be compared to Naïve Geography descriptions of the valley and to the morphometric feature classification (Wood 1996).

4.4.1 Comparison to Naïve Geography sources

The following excerpt is our translation of the entry in the German-speaking Wikipedia article "Gürbetal" (Gürbe valley; Wikipedia DE 2008):

> *"The Gürbe valley is the region between Bern and Thun (west of the Aare) in Switzerland. It encompasses the district of Seftigen and neighbouring municipalities. The valley is named after the river Gürbe. The largest town in the valley is Belp. The Gürbe and Aare valleys are separated by Belpberg (a ridge). To the west, the Gürbe valley is bordered by Längenberg. The flat Gürbe valley floor has a width of between 1 and 2 km and is intensively farmed."*

Fig. 36 shows a depiction of the most important elements in the Wikipedia article along with the delineation of the valley floor. In the western part of the area is the River Gürbe, in the eastern part the river Aare flows out of Lake Thun. North of Belp the Gürbe flows into the Aare which then in turn flows through Bern. As can be seen in Fig. 36, Wikipedia's description of the ridge Belpberg separating the Gürbe valley from the Aare valley somewhat contradicts the assertion that the Gürbe valley is the region bordering the Aare from the west or encompasses the district of Seftigen (whose eastern border is in fact the Aare). However, the width of the Gürbe valley specified by Wikipedia to be 1 to 2 kilometres closely matches the area our DEM-based algorithm delineated as valley floor.

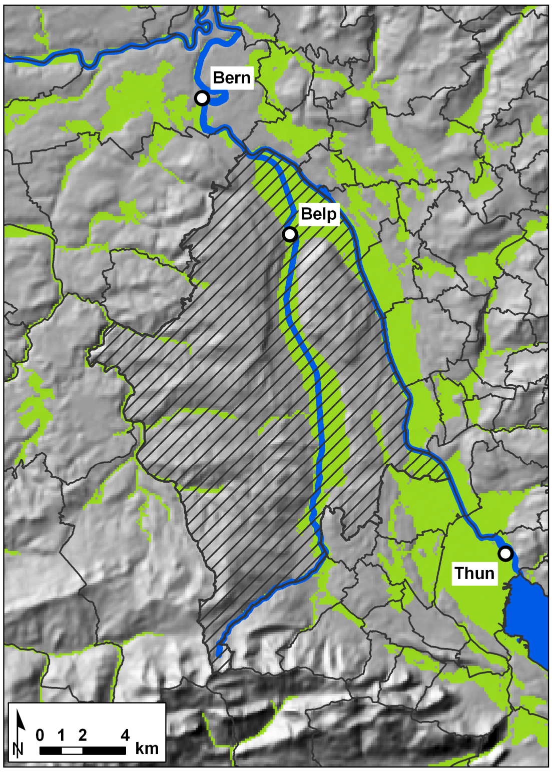


Fig. 36: Characterisation of the Gürbe valley in the German-speaking Wikipedia. Black linear features are administrative boundaries (hatched polygon in the middle: district of Seftigen; others: adjacent municipalities), blue features are water bodies. Background is a hillshaded DEM with delineated valley floors superimposed in light green.

The boxes in Fig. 37 mark the extent of toponym labels mentioned in the Wikipedia article signifying the Längenberg, the Gürbe valley and the Belpberg (from east to west) as extracted from Swiss 1:25,000, 1:50,000 and 1:100,000 maps. Note how the Belpberg toponym labels indeed flank those of the Gürbe valley and the adjacent delineated valley floor of the Aare valley. The boundary of the district of Seftigen, however, contains Belpberg and can thus be deemed to be – at least in this region – too wide an approximation to the Gürbe valley.

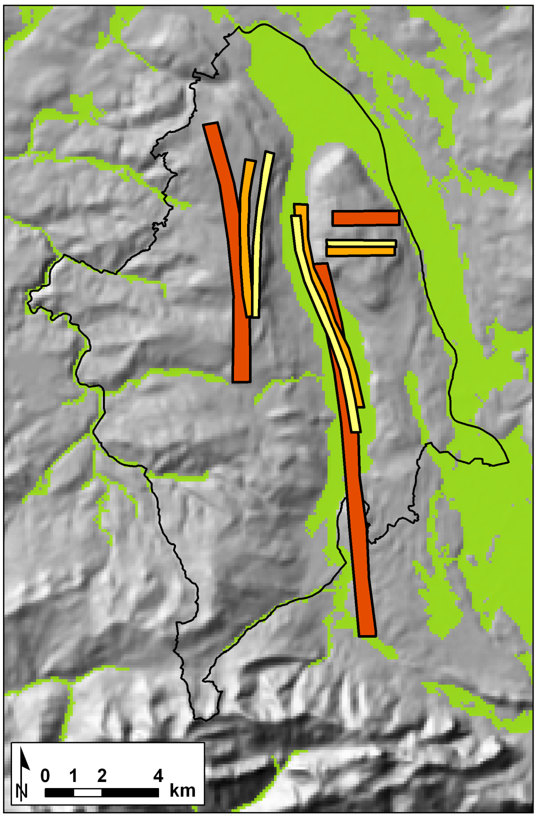


Fig. 37: Outline of toponym labels of Swisstopo maps 1:25,000 (yellow), 1:50,000 (orange) and 1:100,000 (red) referring to Längenberg (west), Gürbe valley (middle) and Belpberg (east). Background: hillshaded DEM, and delineated valley floor, district of Seftigen (black outline) for reference.

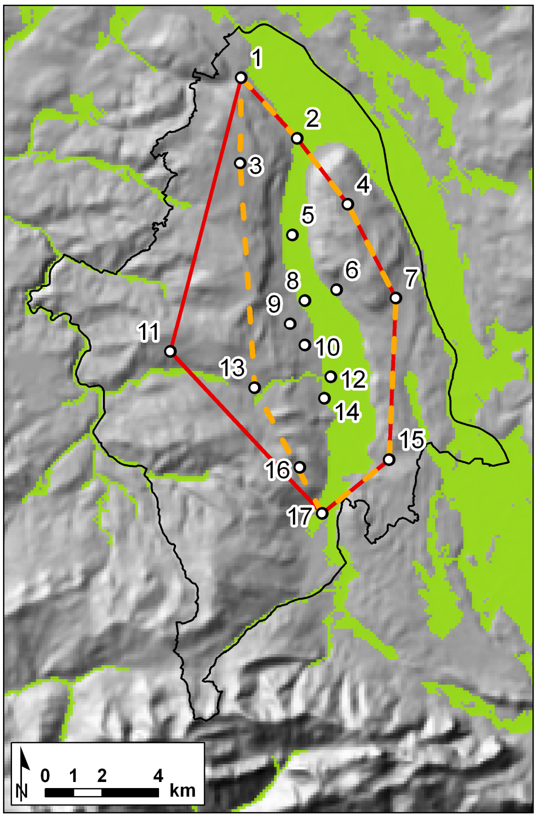


Fig. 38: Municipalities listed as belonging to the Gürbe valley by the tourism organisation of the region together with a convex hull (1: Kehrsatz, 2: Belp, 3: Zimmerwald, 4: Belpberg, 5: Toffen, 6: Gelterfingen, 7: Gerzensee, 8: Kaufdorf, 9: Rümligen, 10: Kirchenthurnen, 11: Rüeggisberg, 12: Mühleturnen, 13: Riggisberg, 14: Lohnstorf, 15: Seftigen, 16: Burgistein, 17: Wattenwil). Background as in Fig. 37.

For cartographic reasons toponym labels may not be placed directly over the objects they signify. Amongst others, the placement is dependent upon factors like contrast of the toponym before the map background and the endeavour not to clutter the map by avoiding overlays of valley toponyms and, for instance, important places such as towns and their toponyms. These considered, toponym label locations and the valley floor delineated coincide well. Interestingly, the 1:100,000 toponym label of Gürbe valley extends significantly further south than toponym labels from larger scales into a region the algorithm also delineated as valley floor.

The apparent uncertainty about the upper end of the Gürbe valley is reinforced by descriptions by the tourism authority of the Gürbe valley. Its website (Verkehrsverband

Region Gürbetal s.a.) lists seventeen municipalities that belong to the Gürbe valley which are shown in Fig. 38 along with their convex hull. This delineation contains large areas of the delineated valley floor and also matches relatively closely the locations of the Gürbe valley toponyms in Fig. 37 – except for the toponym of 1:100,000 which extends considerably further south and the municipality of Rüeggisberg which, judged from the toponyms is west of Längenberg.

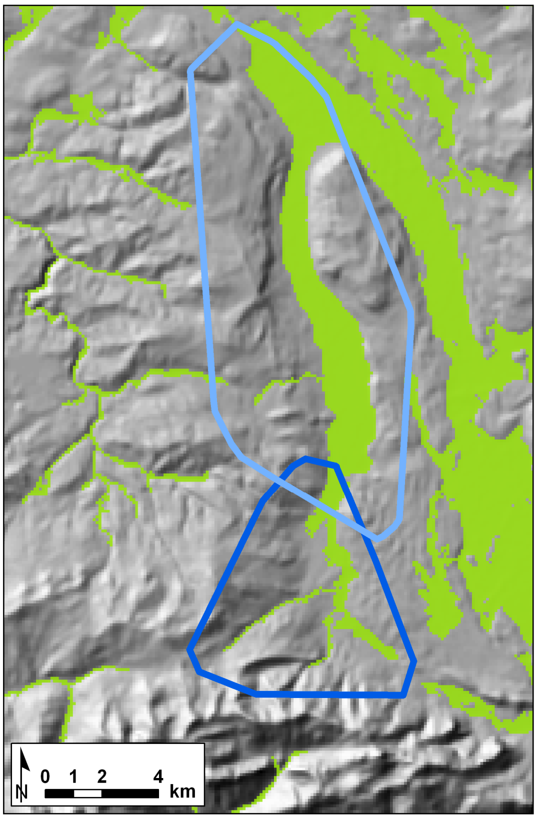


Fig. 39 (left): Convex hulls around rivers and streams assigned to lower Gürbe valley (light blue outline) and upper Gürbe valley (dark blue outline).

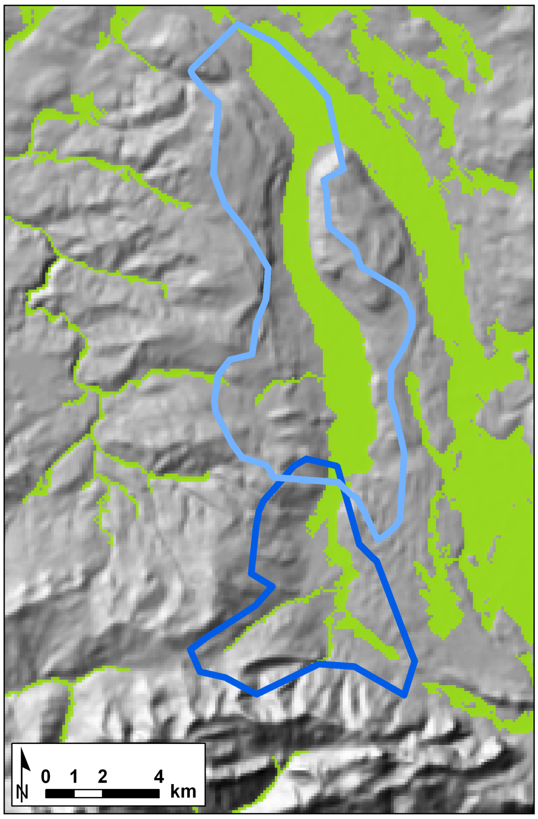


Fig. 40 (right): Hulls around rivers and streams assigned to lower Gürbe valley (light blue outline) and upper Gürbe valley (dark blue outline). For this representation hulls were allowed to have concave parts and were designed to closely follow the upper ends of rivers and streams.

Supplementary hydrologic data on the ecomorphology of streams and rivers from the Geoinformation Office of the Canton of Berne (s.a.) hints at a possible reason for the afore-mentioned uncertainty. In their dataset the hydrology office of the canton of Berne distinguish two areas of the Gürbe catchment (Figs. 39 and 40). Rivers and streams in the Gürbe region are classified as pertaining to either the "lower" or the "upper Gürbe valley". It seems well possible that the lower Gürbe valley is viewed to be more the core of what people term Gürbe valley than the upper part of the catchment. Also, the lower Gürbe valley coincides remarkably well with the convex hull drawn around the principal towns or villages of the municipalities listed as belonging to the Gürbe valley. Consequentially, the economic and population focus of the Gürbe valley is biased towards the lower regions of the Gürbe catchment, thus possibly affecting the notion of the valley as a whole.

4.4.2 Comparison to a classical geomorphometric classification

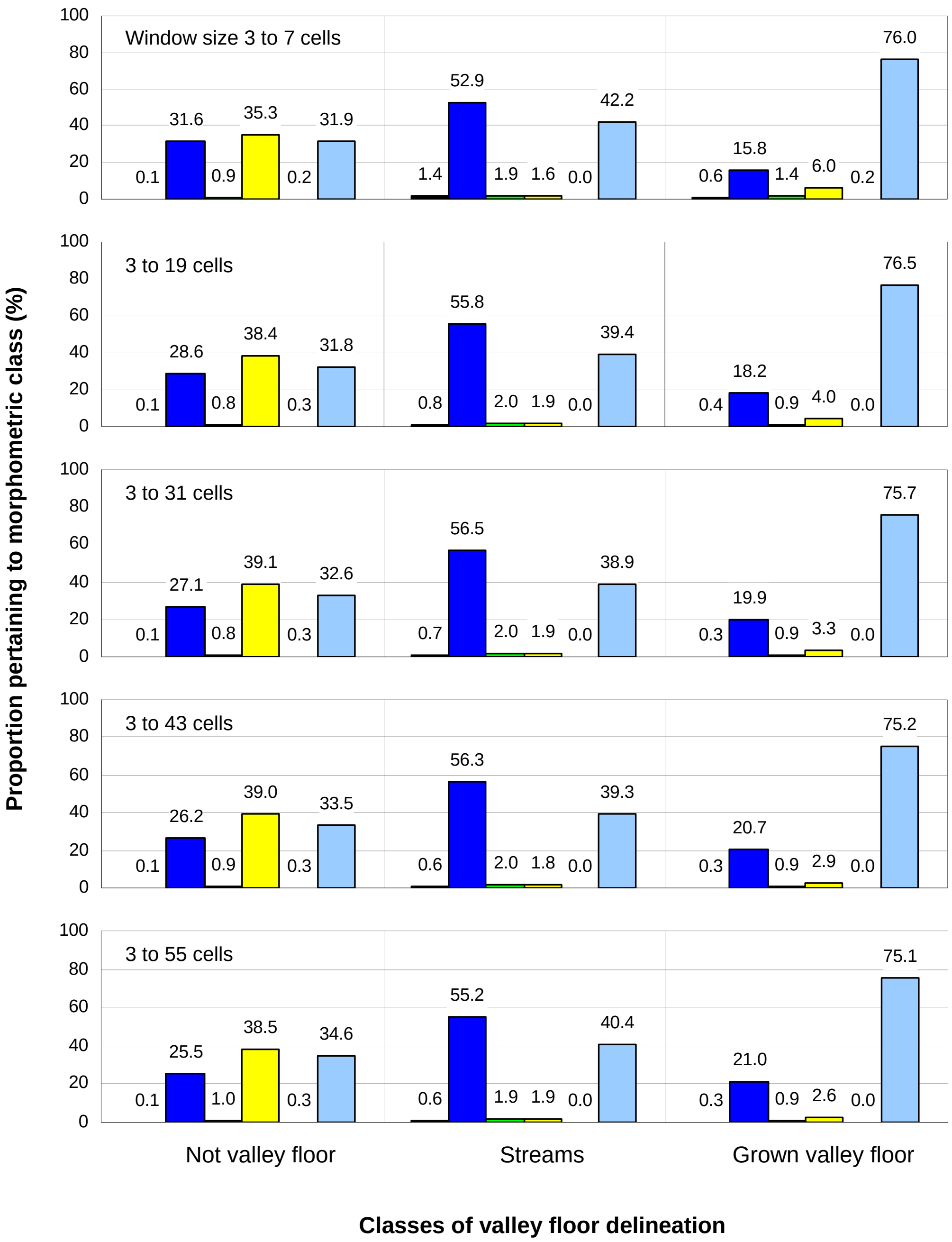


Fig. 41: Proportions of morphometric feature classes computed over different window size ranges per valley floor delineation class. The latter are ordered from left to right: pit, channel, pass, ridge, peak, planar.

For comparison, the six morphometric classes (Wood 1996) were computed for the whole region shown in Fig. 35 (Switzerland and surroundings). In order to exploit the multi-scale properties of landform elements we decided to compute classifications over various window size ranges for implicit surface fitting ranging from 3 cells to 7, 19, 31 43 and 55 cells, respectively. Figs. 41 and 42 show cross-tabulations between the classification by the valley floor delineation algorithm into streams, valley floor and areas not deemed to be valley floor and the six-fold morphometric classification with thresholds {1.5°; 0.1}.

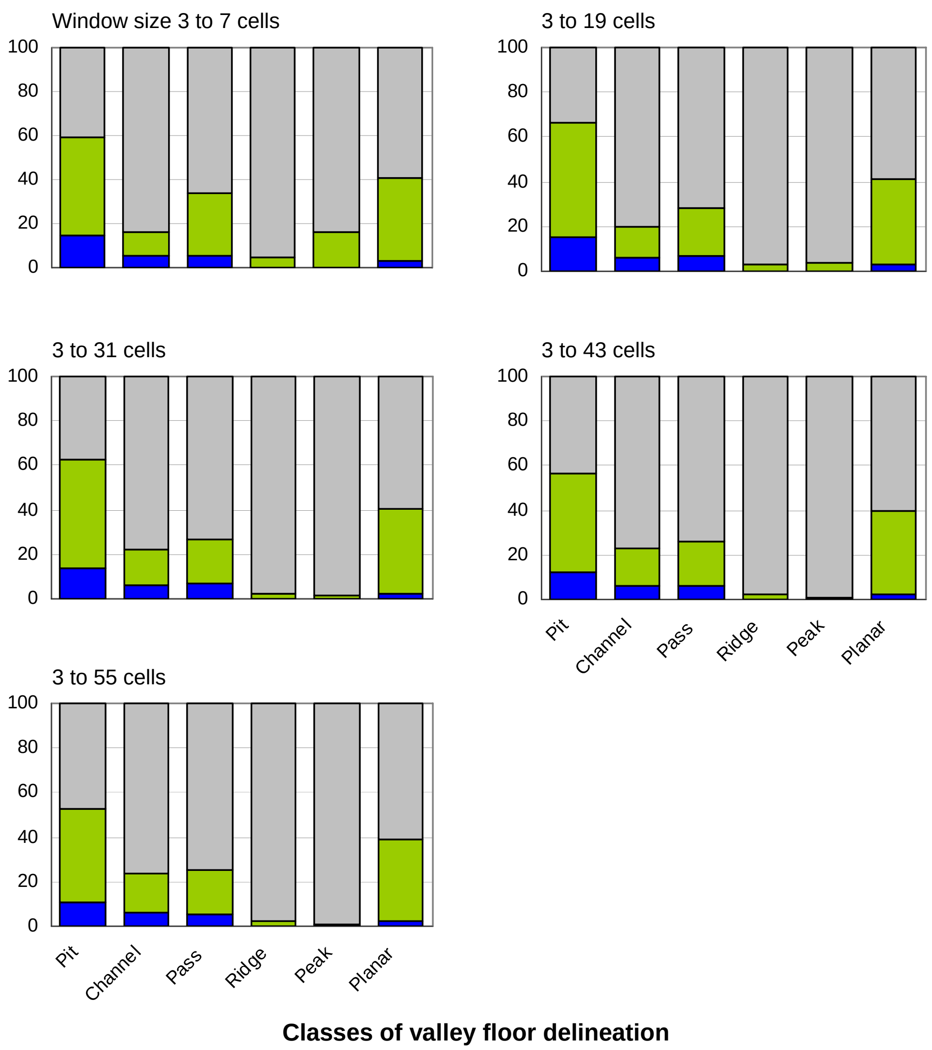


Fig. 42: Proportions of valley floor delineation classes per morphometric feature class. Blue: channel, green: grown valley floor, grey: non-valley floor.

In Fig. 41, areas not classified as valley floors have almost equal proportions of channel, ridge and planar pixels. This is in clear contrast to streams where channel pixels dominate and almost no ridge pixels occur and to the valley floors where there is a clear dominance of planar pixels (from small to large windows: 76–75%), followed by channel (15–21%)

and ridge (6–3%) pixels. With increasing window sizes the proportion of channel cells in the valley floor grows, while it declines in non-valley floor. In terms of other morphometric feature classes, grown valley floor's proportion of peak, ridge, pit and pass diminish more or less clearly with increasing window sizes.

In Fig. 42, a significant proportion of the pits, channels, ridges and passes are shown to be located within the grown valley floor. While with increasing window size the proportion of pits and passes decreases, that of channels grows from 11 to 17%, while the proportion of planar features in the valley floor remains quite stable. Interestingly, there is a significant proportion of peak and ridge elements in the valley floor predominantly at small window sizes (16% and 4%, respectively, for windows ranging from 3 to 7 cells). However, these proportions quickly decrease with growing window size – less so for ridges (4–2%) than for peaks (16–1%), however.

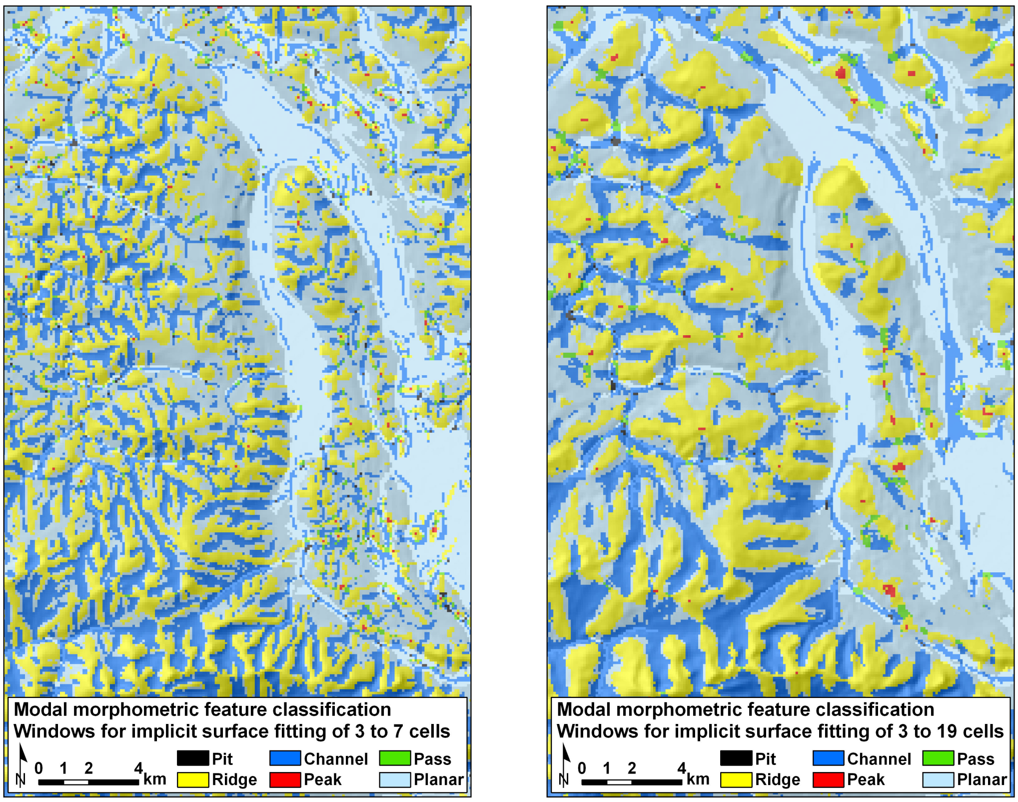


Fig. 43: Morphometric feature classification (semi-transparent) with thresholds {1.5°; 0.1}, over hillshaded DEM and delineated valley floor (white), computed over 3 to 7 cells (left) and 3 to 19 cells (right).

Figs. 43 to 45 show the spatial arrangement of the delineated valley floor with respect to the morphometric classification. Fig. 43 (left; and to a lesser degree, right) shows many channel features on the valley floor, however, their location along the lower end of the valley side slopes suggests that these are primarily artefacts occurring near the concavity of the transition from valley floor to side slopes. While not easily visible in the figures, pits are found throughout the valley floor, often as individual pixels and often close to channel features. Fig. 43 shows that there are several instances of ridge and pass pixels (and for Fig. 43 (left) also some peak pixels) located within the delineated valley floor mainly (but not exclusively) of the Aare valley. These stem from minor surface undulations which in the valley floor delineation were, from the perspective of some seed pixels, sufficiently smooth to be classified as valley floor.

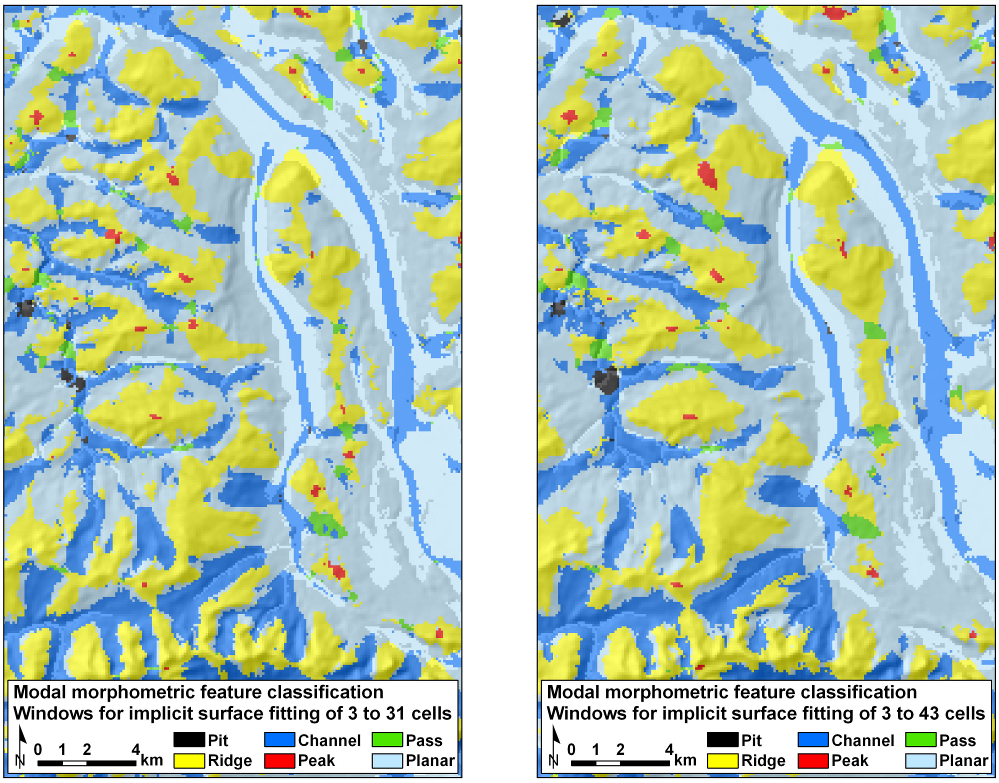


Fig. 44: Morphometric feature classification (semi-transparent) with thresholds {1.5°; 0.1}, over hillshaded DEM and delineated valley floor (white), computed over 3 to 31 cells (left) and 3 to 43 cells (right).

In Figs. 44 and 45 these elements are mostly gone, however, some pass pixels remain classified in the valley floor even at the largest window size. With growing window size the morphometric feature classification picks up the centreline of the two valleys as channel elements. However, the whole delineated valley floor in the Gürbe valley is never classified as channel, nor is it linked to the Aare valley at the confluence. However, much smaller but relief-wise more pronounced valleys to the west of Gürbe valley and also the funnel like headwater region of the Gürbe and a neighbouring topographic depression are picked up very strongly as channel elements; while the main axes of the Gürbe and Aare valley are to a significant amount made up of planar elements. Also, at larger scales significant areas at the confluence of two or several valleys are sometimes classified as large pits.

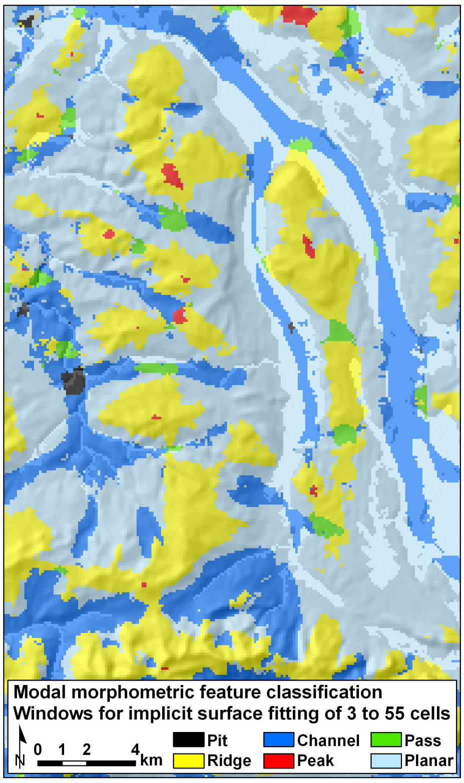


Fig. 45: Morphometric feature classification (semi-transparent) with thresholds {1.5°; 0.1}, over hillshaded DEM and delineated valley floor (white), computed over 3 to 55 cells.

Figs. 46 and 47 show in a more focussed manner only the channelness rather than the modal morphometric feature class. The computation was done with the same thresholds ({1.5°; 0.1}) and using window sizes from 3 to 55 and from 3 to 111 cells. Similar to Figs. 43 through 45, in Fig. 46 (window size up to 55 cells) one can see that the channelness is not high throughout the whole extent of the valleys. For both the Gürbe and the Aare valley there are significant areas which have very low (down to 0) channelness values. If one considers exclusively the membership function to the channel class and classifies it into quartiles (Fig. 46 right) the pattern of channel elements is even more sparse than in the modal morphometric feature class maps.

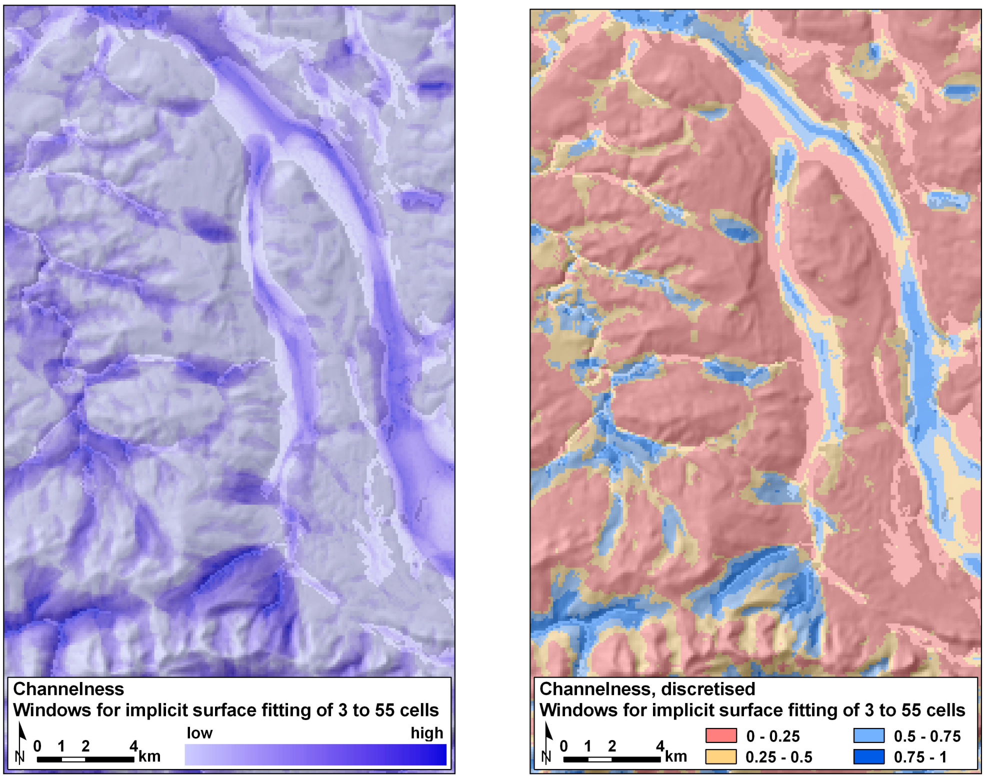


Fig. 46: Channelness computed using thresholds {1.5°; 0.1}, over hillshaded DEM and delineated valley floor (white) (left) and discretised into equally sized classes (right), both computed over window sizes of 3 to 55 cells.

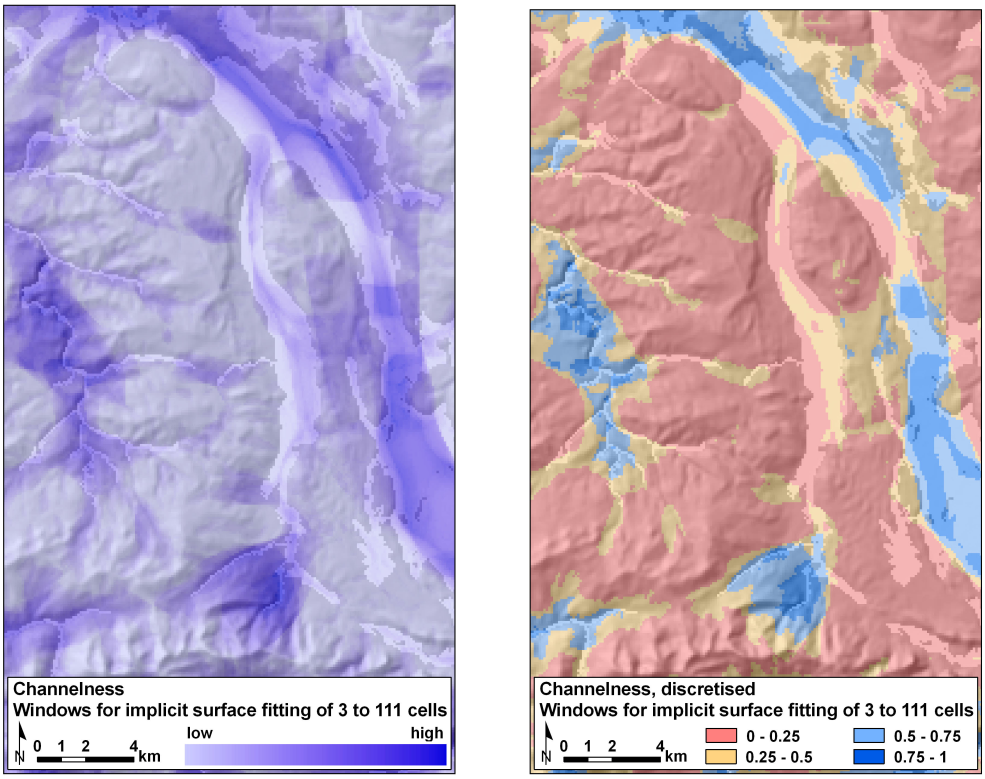


Fig. 47: Channelness computed using thresholds {1.5°; 0.1}, over hillshaded DEM and delineated valley floor (white) (left) and discretised into equally sized classes (right), both computed over window sizes of 3 to 111 cells.

Fig. 47 shows the same datasets computed over yet a larger neighbourhood (window size up to 111 cells), however, the results have not improved. In Fig. 47 (right) the Gürbe valley floor is nigh undetectable except for the funnel-shaped headwater part. The smaller valleys to the west get more or less lumped together into one rather areal feature. Larger parts of the Aare valley floor are picked up, however, but all valley floor parts are not connected. Looking especially at continuously displayed channelness (Fig. 47 left), one can also see artefacts arising from the various implicit surface fittings, for example breaks of channelness in the x and y direction.

Summarising, the classifications of morphometric features suggest that the attributes of our valley floor delineation algorithm at a pixel level make sense (relative dominance of channel and planar features in streams and valley floors). Further, minor ridges and peaks (which may well be glacial features such as the remains of moraines or eskers) are identified by the valley floor delineation algorithm as belonging to the valley floor. This suggests a potential strength of the approach, where the delineation of a relatively simple landform such as valley floor may not easily be reproduced by extending a pixel-based morphometric classification (e.g. through subsequent application of a gradient threshold on planar features).

Some limitations of the multiscale morphometric feature classification method have been shown as well. Generally, the choice of an appropriate analysis window size (range) is not easily made in an informed way and such that it is adequate over the whole of a study area. Also, the algorithm's results may sometimes exhibit quite abrupt changes in values.

Certainly some of the drawbacks could be alleviated by investing more time to fine-tune the algorithm's parameters and probably through the use of a distance decay function in surface fitting. Also, some ideas from Wood (1998; e.g. the inclusion of a specific region of interest) have not been explored in detail. While that latter approach may improve the continuity of, for example, channel features, they would still "not necessarily form a connected network" (ibid: 732).

Possibly, interesting results could come from a combination of the morphometric feature classification method with our valley floor delineation, representing some simple higher level algorithm.

4.4.3 Limitations and extensibility of the approach

An obvious limitation of the valley floor delineation algorithm is the adoption of a single universal gradient threshold for the extraction of valley floors. While the quality of the results can be judged visually, there is no clear indication of a universally applicable threshold to be obtained from the literature or from anywhere else. A possible extension of the approach could select a threshold based upon some contextual information, a lower gradient threshold for lower order (and usually less incised) streams or the tuning of the threshold with some property of the respective drainage sub-basin. However, while such a procedure might improve results it would also introduce additional ambiguity in the form of new parameters.

As for the multiscale morphometric feature classification, the combination of the valley floor delineation algorithm (or in fact, every higher level algorithm) with morphometric features may open up some interesting insights. We hinted at the possibility of, for example, intersecting delineated valley floor with ridge elements to find candidate pixels for eskers or moraines and the like.

4.5 Conclusions

The aim of this case study was to develop a robust method, capable of deriving valley floor extents over a large area. The developed method is top-down and object-based – that is to say it uses definitions of valley floors in the algorithm development and grows contiguous regions which are considered to be valley floor and can be regarded as objects.

To assess the method, given the fiat nature of landforms, we compared the extents of valleys derived from Naïve Geography sources with valley floors from the algorithm. Using the Gürbe valley in Switzerland as an example, comparisons show a relatively good agreement between the vernacular region associated with the Gürbe valley from a variety of sources and the valley floor delineated using our DEM-based algorithm. Additionally, the latter was compared to a rather bottom-up approach which classifies a DEM into six morphometric classes. This comparison showed that the delineated valley floors had differing distributions of morphometric classes from non-valley floor areas (primarily planar slopes and channels), though the algorithm was capable of classifying pixels identified as ridges and peaks as belonging to the valley floor.

More generally, it appears that valleys and associated landforms, or topographic depressions, have gained less attention in the literature than, for example, topographic eminences. An obvious research direction is thus the analysis of valley side slopes. Such approach can lead to a method for characterising topographic depressions and possibly delineating their extents. We will treat such a piece of research in the third case study in Chapter 6. Before that, however, the applicability of our valley floor delineation algorithm to a geomorphological problem domain will be tested in the next case study in Chapter 5.

"That morning he ventured forth, snow had fallen during the night, bright sunshine lay over the valley, but the countryside further off half in fog. He soon left the path, up a gentle slope, no trace of footprints anymore, past a forest of firs, the sun chiseling the crystals, the snow fine and powdery, here and there the faint tracks of game leading into the mountains."

from *Lenz* by Georg Büchner

5 Delineation of valley floors for the quantification of sediment storage

5.1 Introduction[3]

A large number of geomorphologic studies have quantified rates of erosion, sediment transport and sediment yield in mountain belts in historic or postglacial times (Church and Slaymaker 1989). However, comparatively few studies have tried to systematically quantify the distribution, volumes or residence times of intermediate sediment storage such as floodplains, terraces, fans, moraines, and landslide debris, which may occupy extensive tracts of mountain rivers (e.g. Wang et al. 2007). However, sediment storage is a key term in the sediment budget; it builds a crucial link between erosion rate and sediment yield (Lu et al. 2005).

The aim of this case study is to objectively quantify the distribution of sediment storage areas and volumes, i.e. to present a method for deriving valley floor areas hosting extensive low-gradient sediment storage from a DEM. Although numerous techniques have been proposed to objectively extract drainage networks from DEMs, there are relatively few suggestions for delineating and quantifying areas of sediment storage. Some approaches regarding the delineation of valley floors and other features pertaining to valleys have been presented and reviewed in Section 4.2. Besides those (which mostly stem from geographic

[3] Chapter 5 is largely based on Straumann and Korup (2009).

information science) there are approaches primarily from the discipline of hydrology, dealing with the related features of floodplains. Some of this research will be briefly reviewed in the subsequent section. Then the problem of sediment storage area delineation at the mountain-belt scale is addressed. The sediment storage area delineation is done over a large area in Europe in order to integrate over a broad range of tectonic, climatic and lithologic conditions. These influence the production, transport and storage of sediment. The study also estimates storage area volumes from the delineated areas and proposes a method to discern bedrock from mixed and alluvial river regimes.

5.2 Background and research gaps

The objective delineation or characterisation of sediment storage areas such as valley floors or related features has received some attention from geographic information science (e.g. Tribe 1991, Chorowicz et al. 1992, Miliaresis and Argialas 1999, Gallant and Dowling 2003; see Section 4.2). Previous work on delineating floodplains for hydrologic and geomorphic purposes has made use mainly of additional field measurements or numerical process modelling yielding, for instance, flood water surfaces (Noman et al. 2001). Noman et al. (2003) proposed a hydrologic approach to delineating floodplains, requiring that flood water levels were available from field measurements or from hydraulic simulations. Smemoe et al. (2007) extended this approach, and treated floodplains not as discrete objects but as maps of superimposed flood probabilities. Simpler approaches were presented by Williams et al. (2000) and Clarke et al. (2008). The former computed small drainage basins for points along rivers. All cells within such a drainage basin which do not lie more than a certain threshold (15 metres in an example) above their pourpoint were included in the "valley-bottom zone". Clarke et al. (2008) estimated valley-floor width as the length of a transect that intersected the valley sides at a height above the channel elevation equal to five times the empirically determined active-channel depth, and valley floor widths were subsequently averaged per reach. However, although sometimes equated, floodplains do not necessarily cover the extent of low-gradient sediment storage of valleys.

At the mountain-belt scale volumetric estimates of dated molasse sediments allow inference of gross deposition and erosion over geological timescales (Kuhlemann et al. 2002). However, few methods exist to objectively delineate and quantify the areas covered by low-gradient sediment storage from a given DEM on a larger scale. Most geomorphologic studies that have attempted to quantify sediment storage in steep upland terrain focused on much smaller areas (Schrott et al. 2003, Kasai et al. 2004, Lancaster and Casebeer 2007), while few are informative about the distribution and relevance of sediment storage at the mountain-belt scale.

This lack of data is a major shortcoming, since valley fills play important geomorphic roles. For example, large intramontane valley fills modulate significantly fluxes of water and sediment and help buffer the geomorphic coupling between hillslopes and river channels. They hence delay the delivery of hillslope debris to the drainage network. Furthermore, on interglacial timescales large valley fills contribute to both reducing the local relief of a valley and protecting underlying bedrock from erosion by fluvial incision and mass wasting processes (Sklar and Dietrich 2001, Korup and Tweed 2007). During glacial-interglacial cycles, the gradual replacement of glacial ice sheets by large bodies of postglacial sediment and vice versa affects glacio-isostatic and erosion-induced uplift, i.e. the rebound of landmass which was formerly depressed by the weight of ice-sheets after the melting of these and the uplift of landmass caused by the removal of material, respectively. Champagnac et al. (2007) showed that about half of the present day vertical movement of the Swiss Alps can be attributed to uplift induced by enhanced Quaternary erosion. Deglaciation in particular may boost sediment yields through the rapid evacuation of large storage volumes. For instance, Koppes and Hallet (2006) found especially high glacial sediment yields for a retreating glacier.

In this regard, data on the spatial pattern and size distribution of sediment storage help set boundary conditions for numerical models of landscape evolution. Most of these models do not explicitly treat effects of large-scale sediment storage, which in formerly glaciated mountain belts should largely reflect the general downstream decrease in transport capacity, superimposed by effects of natural dams and glacially overdeepened bedrock basins (Korup and Tweed 2007). Empirical evidence suggests that larger drainage basins can produce and store more postglacial sediment than smaller ones on average (e.g. Hinderer 2001, Korup and Schlunegger 2009). However, to our best knowledge, patterns of sediment storage at the mountain-belt scale have so far not been quantified.

5.3 Methodology

Our study area occupies a large portion of the European Alps (Fig. 49). During the last glaciation, the Alps were covered by large ice streams, which extended well beyond the mountain-range front, where large lakes attest to the terminal positions of valley glaciers. Only few mountain peaks remained ice-free, while glaciers scoured valleys to bedrock. Therefore, all sediment accumulated in these valleys is assumed to be lateglacial to post-glacial in age (Hinderer 2001).

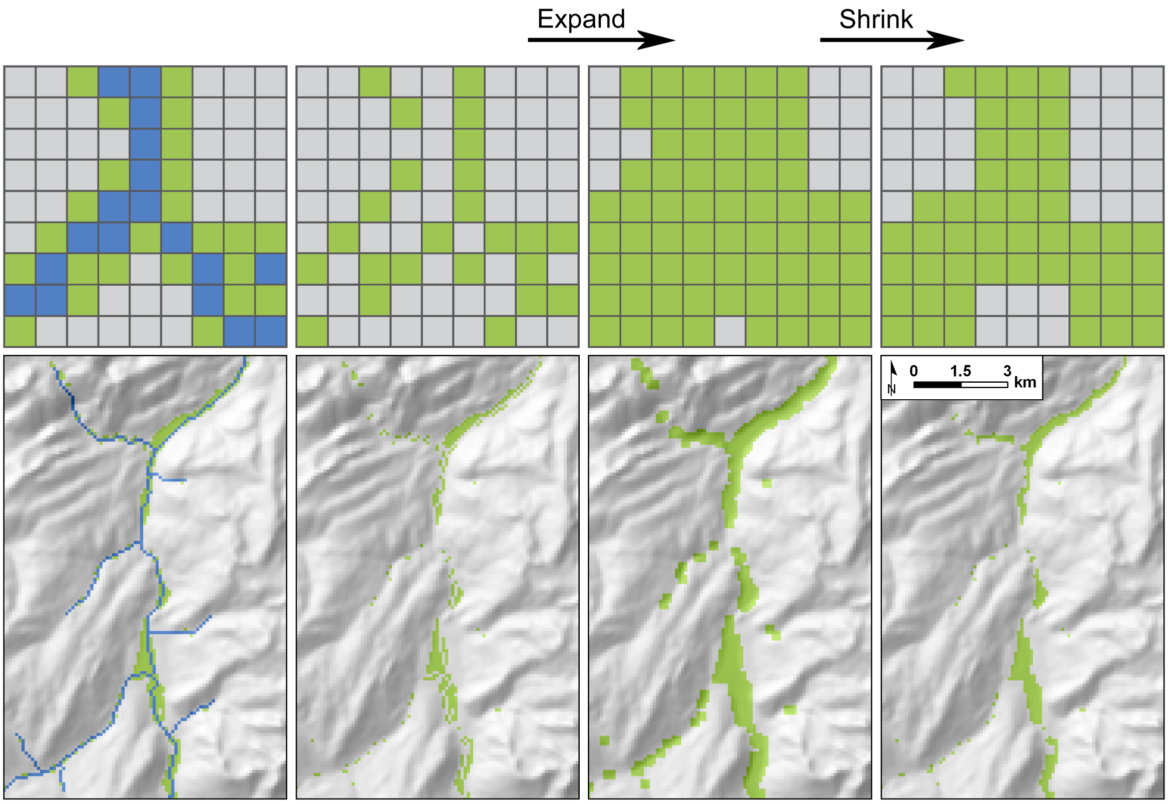


Fig. 48: Application of expand and shrink procedure on the algorithm's result: Algorithmically delineated A_S cells (green) with stream network (blue) (far left); A_S cells only (left); A_S cells grown in all directions by one pixel (right); Grown A_S cells shrunk in all directions by one pixel yielding distinct patches of A_S (far right). Note that edge effects are present in the upper display; in the applied example where valley floor does not usually touch the margins, the shape preservation of the result will be better on average.

For the sake of our approach, it was assumed that individual areas of sediment storage A_S can be characterized as low-gradient terrain adjacent to the channel network. As source data a hole-filled version of the Shuttle Radar Topography Mission DEM (SRTM version 3; Jarvis et al. 2006) was projected into Swiss National Grid coordinates and resampled to 100 metres resolution. For delineating the mountainous portion of the Alps the DEM was subjected to resampling to 1 kilometre resolution. Using this coarse DEM local relief H was computed as the maximum elevation range in a circular neighbourhood of 15 km radius. Areas where $H > 1{,}200$ metres were arbitrarily classified as belonging to the Alps (Fig. 49). In order to yield consistent results and a coherent study area, six small island polygons of 1–35 km^2 were manually reassigned.

The delineation of sediment storage areas was done as described in the first case study in Section 4.3. Sediment storage area (A_S) cells were then post-processed using expand/dilation and shrink/erosion procedures from mathematical morphology combined into what is termed a closing operation (Nagelschmidt Rodrigues et al. 1997). This post-processing step generated individual patches of A_S instead of a single network feature of A_S connected through channel cells (Fig. 48) and thus allowed quantifying A_S without the effect of channel cells having no adjacent A_S. For the subsequent analyses the raster of A_S was clipped with the delineation of the Alps.

5.4 Results

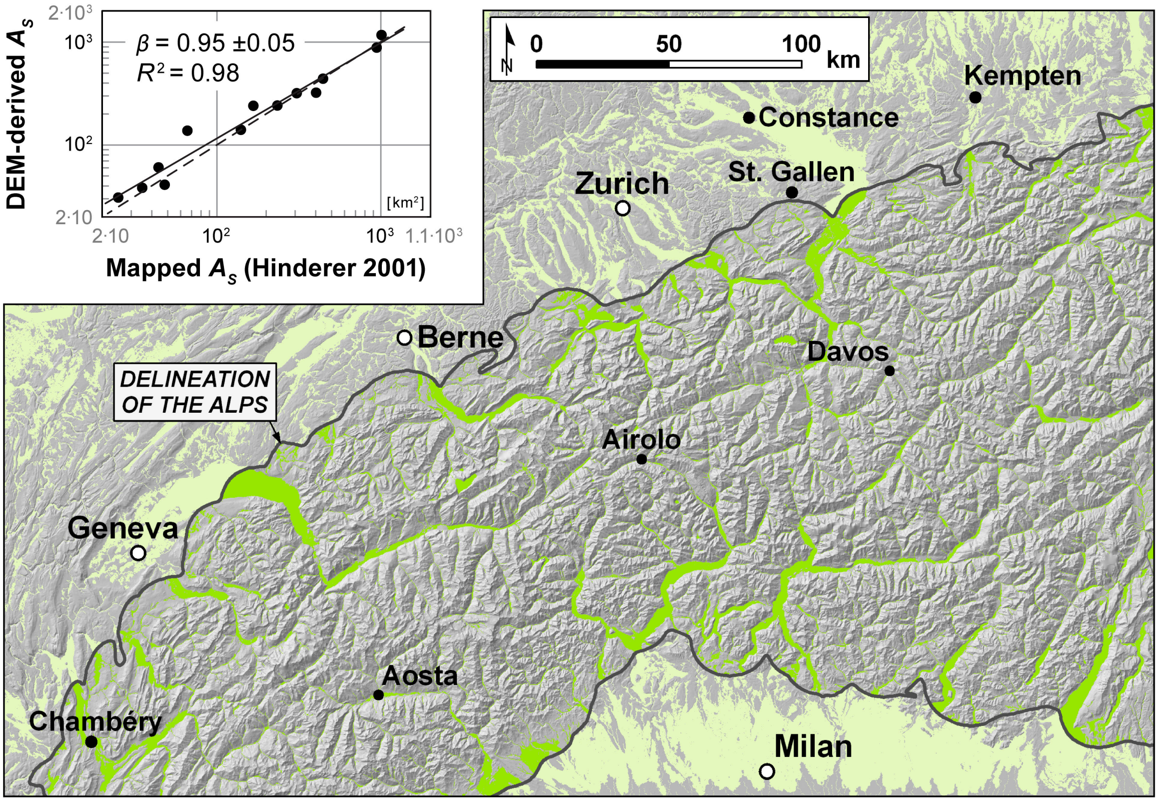


Fig. 49: Overview map of the delineated sediment storage areas A_s in green with the delineation of the Alps. Inset: Comparison with Hinderer's (2001) data, reduced major axis regression line and 1:1 line (dashed).

Our method produced $n = 17{,}766$ individual polygons of postglacial sediment storage within the extent of the delineation of the Alps comprising fluvial valley fills and lakes. The delineated sediment areas cover 5,092 km^2 in total, which equates to about 7% of the study area in the European Alps (65,940 km^2; Fig. 49).

For a given drainage basin area, this first-order estimate compares very well with valley fills which were independently mapped by Hinderer (2001; inset in Fig. 49). A linear relationship was not expected, as the mapped areas of Hinderer (2001) also include large tributary fans, whereas the resolution of the approach at hand may overestimate sediment storage in low-order basins. The reduced major axis regression (Mark and Church 1977) between the DEM-derived A_S and the A_S by Hinderer (2001) has indeed a slope which is slightly below 1 (though the confidence interval does include 1). The regression has a very high coefficient of determination of 0.98.

As another means of validation the resulting delineation of A_S was overlaid with a digital representation of the Swiss geotechnical map (Schweizerische Geotechnische Kommission 1963–1967; scale 1:200,000). Fig. 50 shows the proportion of the total study area pertaining to sediment storage area stratified into different categories of the geotechnical map. Comparing the other bars with the rightmost bar, it is obvious that lakes and loose superficial formations (categories 1 and 3–7) are over-represented in sediment storage areas while glaciers and rock (categories 2 and 8–30) are overrepresented in non-sediment storage areas. Unfortunately, breaking this statistic down into single categories is not universally sensible since some categories are homogeneous enough to allow them to be sensibly found in both sediment storage and non-sediment storage areas. This is exemplified by, for instance, category 3 which is described as a mixture of sand to silt often with detritus stemming from either ground or other moraines. This category exhibits a range of slope gradient of 0–75° with a mean of 18.5°. Still, generally, the comparison with the geotectonic map further testifies to the consistency of the delineation of A_S.

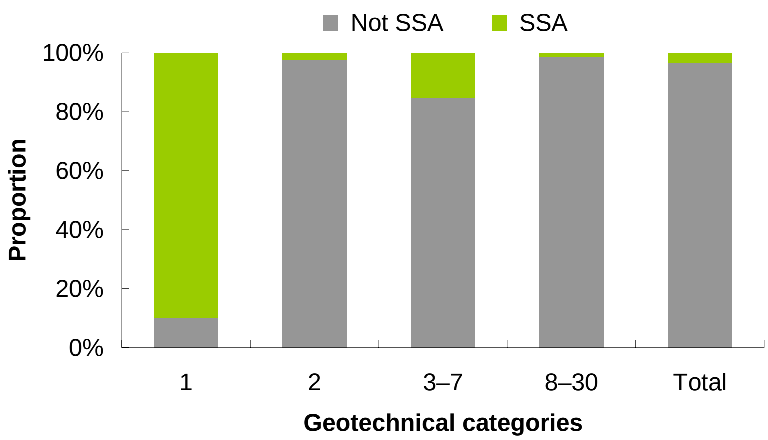


Fig. 50: Proportion of geotechnical categories in the study area allocated in sediment storage area (A_S, green) and outside (not A_S, grey) classes. 1: Lakes, 2: Glaciers, 3-7: Loose superficial formations, 8-30: Rock.

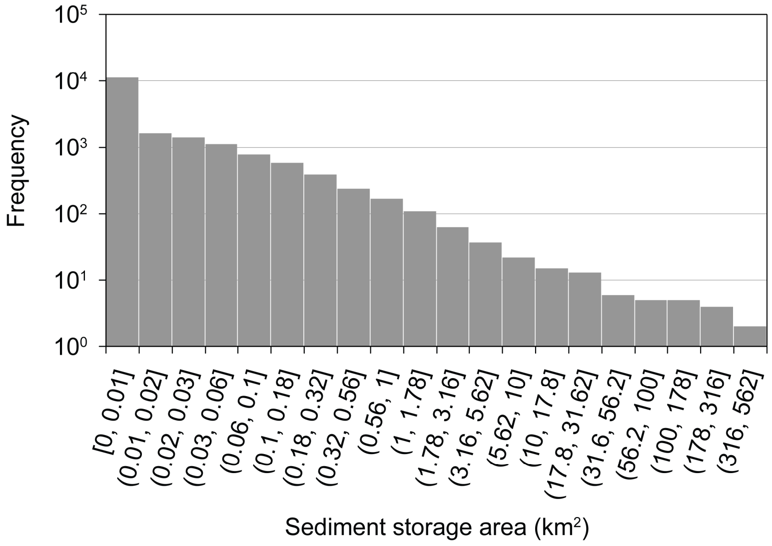


Fig. 51: Histogram sediment storage area units in the Alps.

In order to characterise the aspatial distribution of sediment storage in the European Alps Fig. 51 shows the size-histogram of the 17,766 individual sediment storage areas. As can be seen, the distribution is very strongly positively skewed (skewness of 43.59; note, both the y-axis and the bins on the x-axis are logarithmic). From the small sediment storage areas there is a more or less smooth decline to the large ones with occasional steps in the distribution. The above distribution is not easily described with standard statistical descriptive measures: all the minimum, the first quartile and the median adopt the smallest possible value of 0.01 km^2 (1 raster cell), the mean is 0.2866 km^2 and the biggest sediment storage unit has an area of 419.9 km^2.

Similarly, Fig. 52 (blue data points, top and right-hand axes) shows the size frequency distribution of the delineated sediment storage areas, A_S, as frequency densities. Therein, A_S has a remarkable power-law trend over four orders of magnitude with a scaling exponent of $b_A = -1.77 \pm 0.03$ ($\pm 1\sigma$).

To estimate also the *volumes* of individual sediment storage units rather than only the areas, the 13 drainage basins which were analysed by Hinderer (2001; inset in Fig. 49) were used. An empirical relationship between the sediment volume V_S and drainage basin area A_C by Hinderer (2001) was used to compute the expected sediment *volumes* of the drainage basins. The total *area* of storage in these basins, A_S, was computed from our data. Finally, V_S was regressed on A_S. The power-law regression between V_S and A_S yielded an exponent $\alpha = 1.12 \pm 0.15$ and a high coefficient of determination (R^2) of 0.78.

The regression between V_S and A_S could then in turn be applied onto all 17,766 of our sediment storage units to compute their volumes. The resulting frequency density distribution of sediment storage volumes, V_S, is also contained in Fig. 52 (red data points, bottom and left-hand axes) and has an exponent $b_V = -1.71 \pm 0.03$.

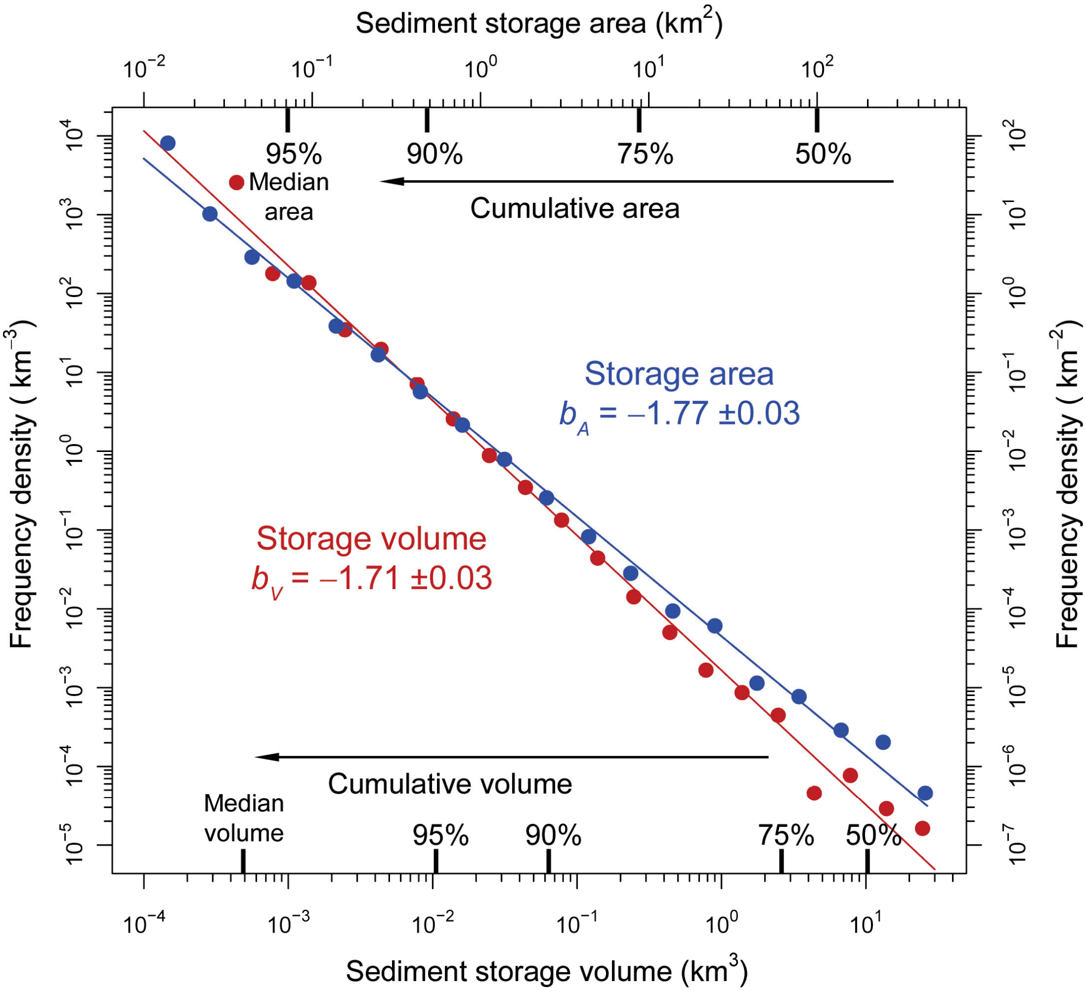


Fig 52: Non-cumulative size-frequency relationships of sediment storage area and volume. The area- and volume-density distributions have power-law trends over four and five orders of magnitude with estimated exponents b_A and b_V, respectively. The volume-density distribution was estimated from regression of total sediment storage volume (Hinderer 2001) and A_S, with randomly iterated values of exponent $\alpha = -1.12 \pm 0.15$ ($\pm 1\sigma$) and intercept $\log y = 1.52 \pm 0.35$.

As the tick marks pertaining to the cumulative sediment storage area in Fig. 52 indicate, the total area covered by sediment is clearly dominated by the larger valley fills, although, frequency-wise, there is an abundance of small A_S (see above and Fig. 51). Half of the sediment storage area is contained in the eleven largest (>100 km^2) fills, i.e. the broad Alpine valley floors feeding into the large glacially scoured lake basins at the mountain front (Fig. 49). Correspondingly, large valley fills also dominate the volumetric distribution of storage (cf. the tick marks pertaining to cumulative storage volume in Fig. 52), with approximately half of all sediment being sequestered in the lower reaches of only nine trunk valleys.

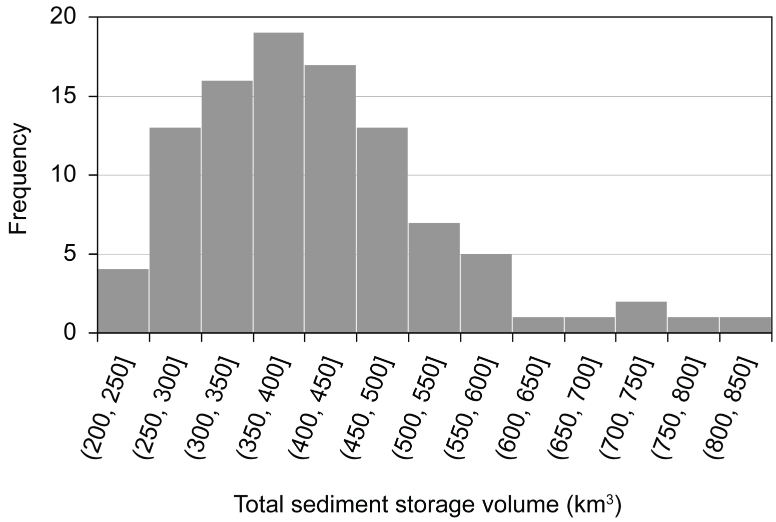


Fig. 53: Histogram of total sediment storage volume derived from 100 Monte Carlo iterations.

In order to quantify the prediction error of this proposed volume-area scaling, $n = 100$ Monte Carlo simulations were run. Each iteration used normally distributed exponent and intercept values for predicting the volume for each individual sediment storage unit. This way, the total volume of postglacial fluvial and lacustrine sediment storage and the associated error could be estimated at 411 ±12 km^3 (±1 standard error) in the study area (Fig. 53 shows the obtained overall distribution).

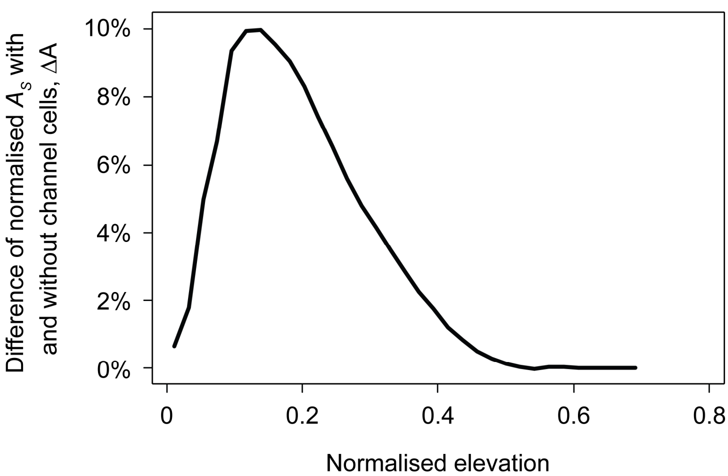


Fig. 54: The difference in normalised A_S including and excluding channel cells (ΔA) in dependence of normalised elevation.

Additionally to above investigations of the spatial and aspatial distributions of sediment storage areas and volumes, hypsometric analyses regarding the distribution of sediment storage over elevation and local relief. These analyses gave an idea about how far downstream the sediment forming fluvial and lacustrine valley fills has been transported since deglaciation. The hypsometric analysis shows that about 90% of the total sediment storage area lies below the 25th percentile of elevation (Fig. 55). The results also highlight that low-gradient fluvial and lacustrine sediment storage in the upper third of the mountain belt is negligible at the scale of this study.

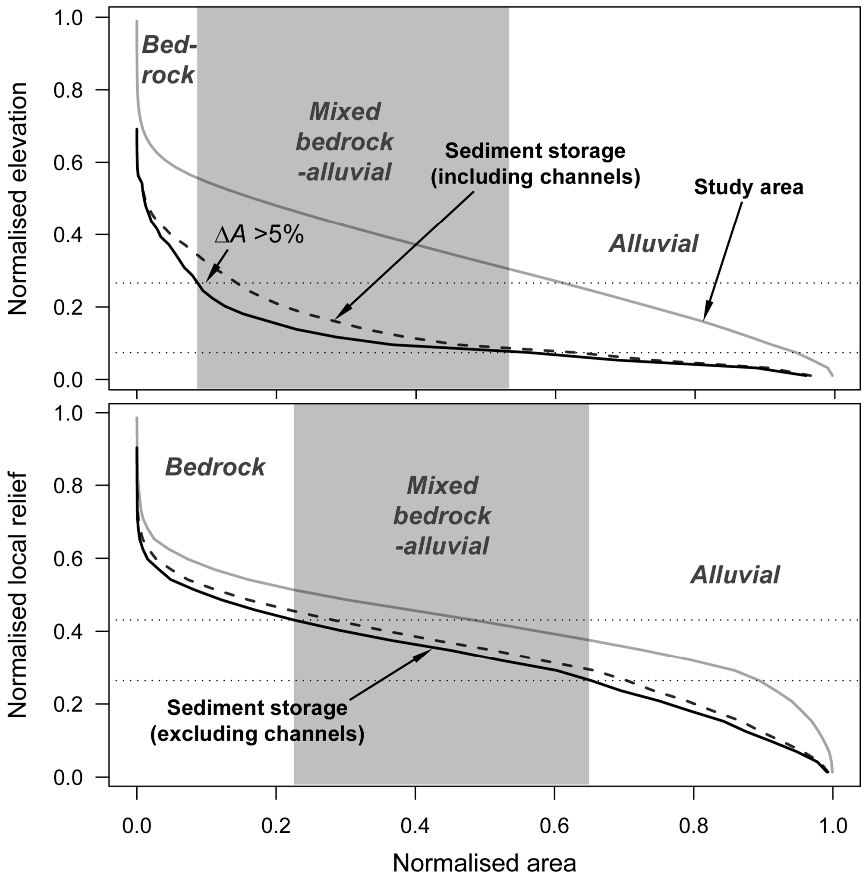


Fig. 55: Hypsometry of the study area (Fig. 49) and of sediment storage areas with and without channels. All curves are normalised to maximum elevation of 4,700 m (top) and hypsometry of local relief *H* (same symbols; normalised to maximum *H* = 3,600 m) (bottom).

However, the question of whether or not to include river channels with adjacent A_S cells as storage elements in this estimate is not trivial. In Section 5.3 we opted for the inclusion of such channels and applied an algorithm from mathematical morphology to clean the A_S raster from river channels with *no* adjacent A_S cells (Fig. 48). Investigating the difference in the hypsometric analyses including and excluding channels *with* adjacent A_S cells gives interesting results, however. For example, the difference in normalised storage area ΔA

made by including river channels with adjacent A_S cells in the storage estimates is > 5% between the 7th and 27th elevation percentile (Fig. 54). In other words, such channel storage appears to have the highest contribution in the lower parts of the mountain belt (cf. also Fig. 55). Moreover, 90% of the total sediment storage area is below the 25th elevation percentile (Fig. 55, top) and below the median local relief (Fig. 55, bottom). This supports the view that most sediment is stored in areas of low erosion, assuming that local relief is a first-order proxy of postglacial erosion rates (e.g. Vance et al. (2003) found a relationship between denudation rate and relief over three orders of magnitude).

The horizontal dotted lines in Fig. 55 bound the elevation range where inclusion of channels as sediment storage leads to > 5% difference in cumulative area, ΔA. We propose that this can be seen as defining a domain where mixed bedrock-alluvial rivers dominate (gray shading in Fig. 55).

In order to investigate the amount of sediment storage in dependence of drainage basin size two different approaches were employed. Firstly, the drainage basins of sediment storage units were derived and analysed, secondly, a random sampling approach of drainage basins was devised.

Fig. 56 shows an overlay of the scatterplot relating sediment storage units to their respective drainage area and a boxplot. Note that only sediment storage units ≥ 0.1 km^2 were used in this plot in order to not clutter the graphic (reduction of about 60% with regard to number of data points, cf. Fig. 51). Clearly, larger sediment storage units feature larger drainage basin areas. This is what one would expect, since in larger drainage basins there is potential to produce and collect a larger amount of debris which can then be transported downstream and be deposited. For the two smallest bins of sediment storage area in Fig. 56 the scatterplot shows an artefact at the lower end of the y-axis; there is only a limited number of points below 5 km^2 drainage basin area. This likely stems from the fact that the delineation algorithm used a channel initiation threshold of 5 km^2 for generating seed cells for the delineation algorithm (see Section 4.3.2).

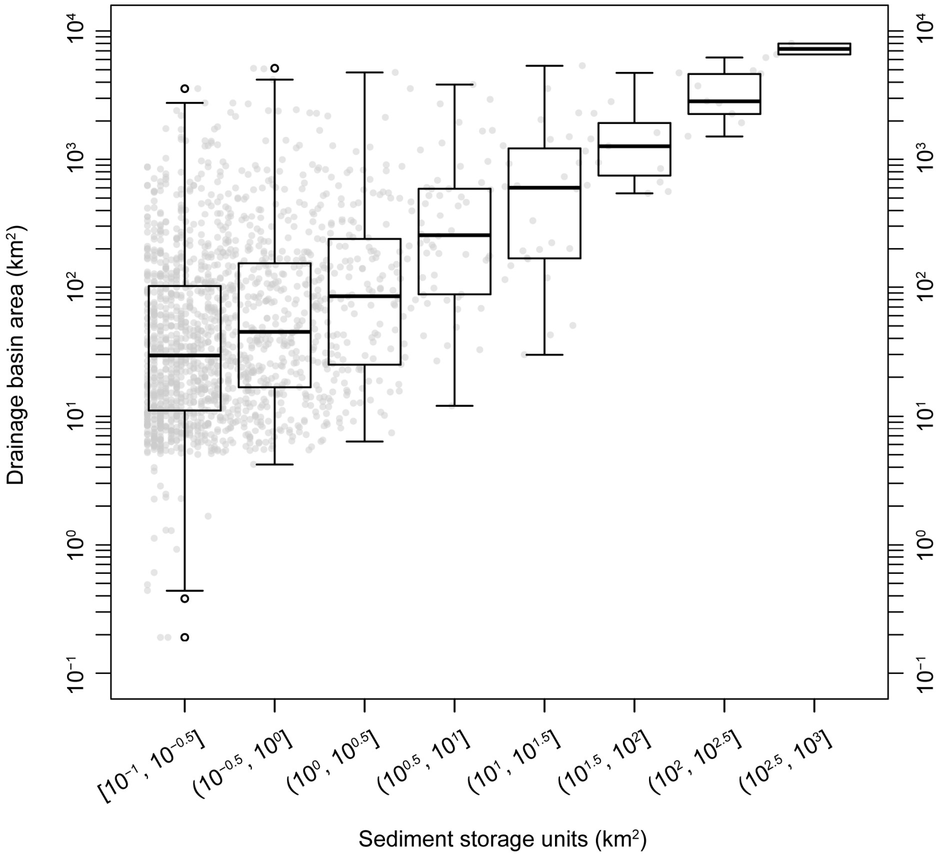


Fig. 56: Boxplots of drainage basin areas of sediment storage units versus the size of the latter. Sediment storage areas < 0.1 km^2 were excluded from this plot.

Above analysis was complemented by a second approach asking what the distribution of sediment storage in randomly sampled drainage basins would look like (rather than the relation of delineated sediment storage units to their drainage basins). In this approach all sediment storage within a certain drainage basin is analysed, while the previous approach exclusively related the furthest downstream sediment storage unit to its drainage area.

For the analysis resulting in Fig. 57 drainage basin outlets were positioned in random manner in the study area. The sampling of these involved stratification according to the order of magnitude of A_C. If there were not such a stratified sampling scheme, the random choice of outlets would have resulted in a sample of largely small drainage basins, since points with relatively small drainage areas are overly abundant compared to those with big drainage areas.

Since there was a lower limit of 5 km^2 for drainage basins in the method for delineating sediment storage areas, this lower limit was also adopted for this investigation. Then, for every order of magnitude drainage basin outlets were randomly positioned (50 for A_C from 5 km^2 to 10 km^2, 100 per order of magnitude above 10 km^2). The subsequent zonal statistical analyses revealed that the area of sediment storage units A_S above 350 such randomly selected drainage basin outlets increases in nonlinear fashion with upstream basin area. Fig. 57 also contains a tentative lower envelope for the sediment storage area in a drainage basin of given size. On average 5.8% (±4.5%) of basins greater than 10 km^2 are covered by fluvial and lacustrine valley fill and the minimum proportion of A_S increases by a factor of about 5 for A_C growing from 10 km^2 to 6,000 km^2.

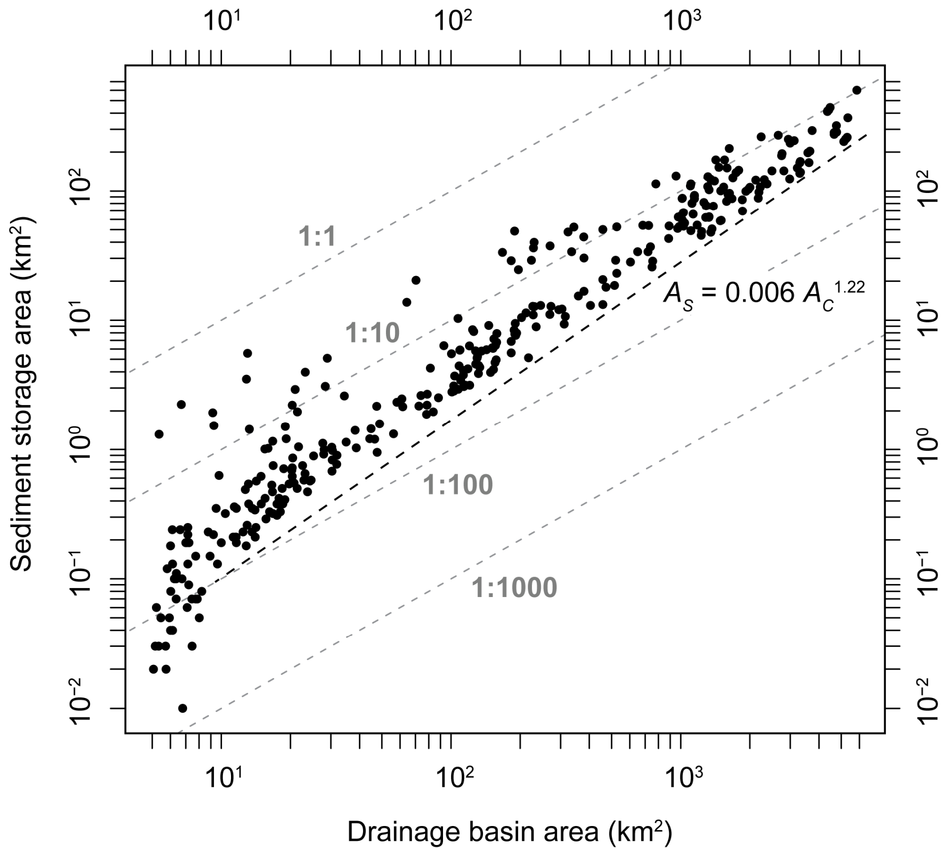


Fig. 57: Random sample of n = 350 drainage basins (A_C >5 km^2) and their DEM-derived areas of sediment storage. Black dashed line is the empirical lower envelope curve, gray dashed lines are ratios A_S/A_C.

Further, Fig. 57 also shows that the fraction of sediment storage of drainage basins varies by three orders of magnitude in small headwater basins (A_C < 10 km^2). These are more prone to episodic sediment pulses and resulting deposition or aggradation and less capable of buffering such episodic disturbances. Besides, the same reasoning regarding the channel initiation threshold of 5 km^2 applies as in the previous analysis.

Lastly, applying spatial algorithms one can try to characterise the confinement of rivers. Consider the map in Fig. 58 where the colours indicate the degree of confinement of a river. This measure was operationalised and computed as follows. First, rasters of relative abundance of grown sediment storage area were generated – in this example – over neighbourhoods of 3 by 3, 5 by 5, 7 by 7 and 9 by 9 cells. The relative abundance in the moving window was computed as the ratio of the number of grown A_S cells in the window, $n(A_S)$, and the maximum potential number of such cells, $N(A_S)$:

$$w_{A_S} = \frac{n(A_S)}{N(A_S)} = \frac{n(A_S)}{n_{tot} - n(S)} \tag{11}$$

where n_{tot} is the total number of cells in the respective neighbourhood and $n(S)$ is the number of stream cells in the neighbourhood.

The confinement measure is then simply the mean of the relative abundances over different neighbourhood sizes. Note that this use of absolutely defined neighbourhoods makes the method – although operating on multiple scales – scale-dependent.

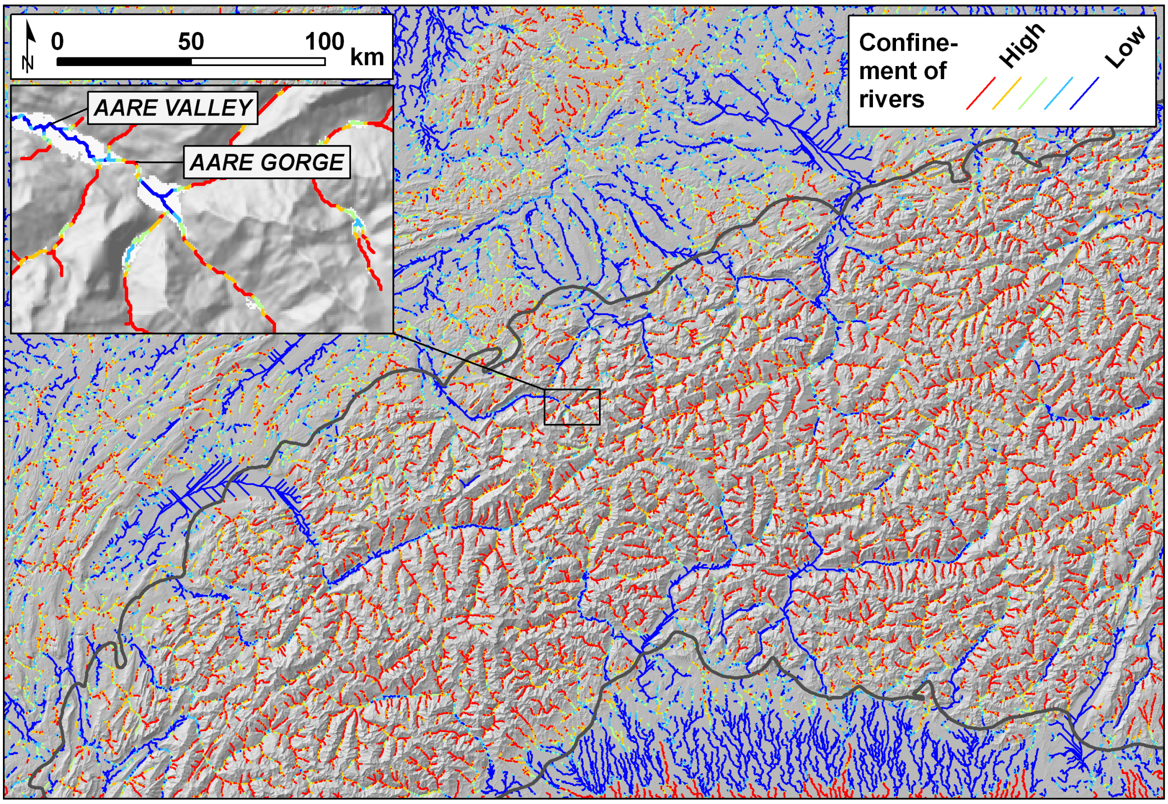


Fig. 58: Confinement of rivers as computed using the sediment storage area delineation.

The map in Fig. 58 shows the streams in the study area coloured according to their confinement measure where this measure was allowed to vary also within a single stream reach. The inset in Fig. 58 includes A_S as white areas. In the depicted region the simple method nicely manages to highlight the Aare gorge in the canton of Berne. How well exactly this method is able to portray characteristics of rivers and also whether there could be improvements over this simple approach has to be further investigated, however.

5.5 Discussion and conclusions

This case study provides one of the first quantitative and solely DEM-derived estimates of postglacial fluvial and lacustrine sediment storage at the mountain-belt scale. The results are first-order estimates and based on several assumptions; nevertheless they agree very well with earlier estimates by Hinderer (2001) without any prior calibration of sediment storage areas (inset in Fig. 49). For a critical appreciation of the use of the SRTM DEM and the discussion of errors in these data see Section 4.3.1.

The results show that the mountain-belt scale pattern and distribution of postglacial sediment storage in the Alps is largely skewed. Most sediment is stored at low elevations (Fig. 55) and in areas of lower local relief and hence – as is hypothesised – low erosion. Larger valleys host the vast majority of postglacial debris (Fig. 52), although, in terms of numbers, there is a big bias towards small sediment storage areas. The dominance of large valleys is probably a result of multiple glacial-interglacial cycles. These processes could create commensurately higher accommodation space through what is termed glacial overdeepening. Glacial overdeepening denotes the formation of a subglacial basin leading to the situation where in some area the glacier bed rises in the direction of ice flow (Alley et al. 1999; cf. Huuse and Lykke-Andersen (2000) who discuss processes which may lead to overdeepening of Quaternary valleys).

Considering the effect of channel storage may allow objective quantification of the downstream transition between three fundamental process domains of the fluvial system (Figs. 54 and 55), i.e. bedrock rivers, mixed bedrock-alluvial rivers and alluvial rivers at the mountain-belt scale. Although the distinction between these domains depends on an arbitrarily defined threshold value of added contribution of channel storage ΔA (5% in the case of Fig. 55), the data indicate that bedrock rivers appear to dominate upper-level and high relief portions of the Alps. This notion must be tested further with field evidence, but the essence of the presented method as a potential predictor of river types remains regardless of the eventual choice of ΔA or resolution.

On a more general note, this case study was capable of demonstrating how our algorithm designed to delineate valley floors from a theory-grounded (top-down) geomorphometric perspective could be used in the context of geomorphology and geology. Interpreting delineated valley floor as areas of low-gradient sediment storage allowed us to link the results of our algorithm devised in Section 4.3.2 to an empirical study by Hinderer (2001). Through this link the relatively simple delineation of sediment storage areas could be extended to estimate sediment storage *volumes* – however, the latter being spatially rather implicit (i.e. the volume of an individual sediment storage unit can be estimated, but not how this volume is distributed spatially within the unit). Towards the end a simple algorithm to assess the confinement of river stretches was sketched out briefly.

Summarising, the employed methodology allowed a study to be carried out over a major part of the European Alps which would not have been feasible using largely manual methods.

"Lenz was uneasy about remaining in the house on his own. The weather had turned mild and he decided to accompany Oberlin into the mountains. On the other side, where the valleys meet the plain, they parted. He returned back alone. He wandered through the mountains this way and that, broad planes inclined into the valleys, little woodland, nothing but powerful lines and in the distance the wide smoky plain, a brisk breeze in the air, nowhere a trace of a man other than here and there an abandoned hut where shepherds spent the summer, aslant on a slope."

from *Lenz* by Georg Büchner

6 Devising and testing valley characterisation algorithms

6.1 Introduction

In this case study a method is suggested to characterise valley sides and, combined with the previously developed valley floor delineation algorithm (see Section 4.3.2), to characterise the valleyness of locations.

Regarding the literature there is not much to add to the body of research that was described in Section 4.2. After the brief section on *Background and research gaps* this chapter will detail the method, before a human-subject experiment is introduced to assess the plausibility and the value of the results.

6.2 Background and research gaps

6.2.1 Characterisation of valleys

To our best knowledge there has been no research into the fuzzy characterisation of valleys. However, an obvious candidate algorithm for such an endeavour is multiscale morphometric feature classification and, specifically the "channelness". Such a method was detailed and applied to Gürbe and Aare valleys in Section 4.4.2, and some drawbacks of the method have been described in said section. Since it has been applied to the fuzzy characterisation of peaks (using the fuzzy “peakness”; Fisher et al. 2004), it is tempting to also apply it to valleys (using the fuzzy “channelness”).

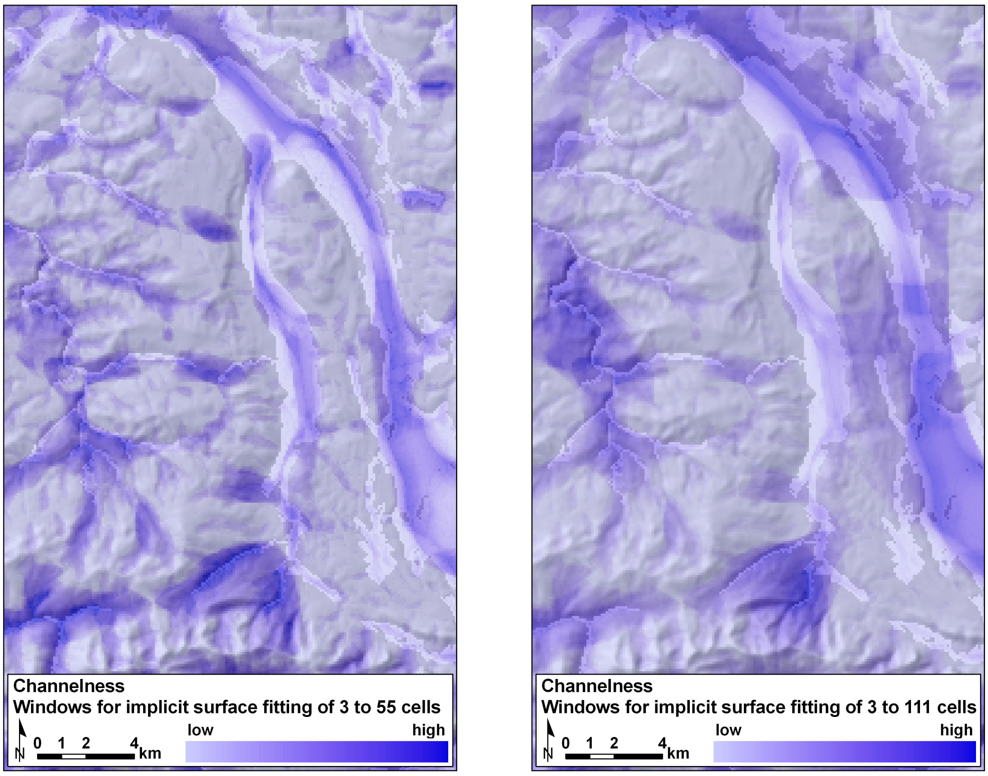


Fig. 58: Channelness computed with thresholds {1.5°; 0.1}, over hillshaded DEM and delineated valley floor (white), computed over 3 to 55 cells (left) and 3 to 111 cells (right).

However, looking at channelness, the method seems rather apt to the characterisation of valley floors, i.e. the relatively flat lowest part in between two valley sides, and not for valleys in their entirety (Fig. 58). This is not surprising recalling the definition of channel features which exhibit either near-zero gradient, near-zero maximum and negative minimum curvature, or positive gradient and negative cross-sectional curvature (Wood 1996). When the moving window for implicit surface computation is roving over valley side slopes, these conditions will seldom be fulfilled. Thus, though tempting to use, the channelness definition has no inherent ability to meaningfully characterise valley side slopes. In what follows, we will thus devise an algorithm to characterise valley side slopes and to eventually yield a measure of valleyness. This measure will then be tested in a human subject experiment.

6.2.2 Conducting questionnaire surveys

Since the algorithmic characterisation of valleys in this chapter is aimed at the human perception and appreciation of this landform, a human-subject experiment was deemed to be suited best to assess the plausibility and value of the algorithmic results. The human subject experiment will take the form of a questionnaire survey which presents participants with photographs as stimuli.

Questionnaires are a popular research instrument in social sciences. As in any human subject study, care has to be given to choose the sample of participants and to address enough people to account for the possibly low response rates.

In constructing the questionnaire itself, several important points need to be considered. For example, responses to closed questions are easier to analyse statistically. A popular way of asking closed questions is to provide participants with what is termed a Likert scale where they can rate their response to a question or stimulus (Trochim 2006). It is considered sensible to include an option “I don’t know” or “No opinion” (Montello and Sutton 2006: 85). Regarding the number of items a range of five to ten (Martin 1996: 21) or five to nine with a preference to the low side (Montello and Sutton 2006: 87) is suggested.

The questions need to be phrased very carefully not to induce a bias in the responses and not to challenge the comprehension by the participants (Martin 1996: 19p). The exact wording can affect results considerably. Martin (1996: 20) mentions an example where 53% of respondents agreed that the government was spending too much money “on welfare”, while only 23% agreed that the government was spending too much money “on assistance to the poor”. Also the order in which the questions and/or stimuli are presented is important, since it may lead to order and context effects. A strategy to overcome these is randomisation (Montello and Sutton 2006: 94). To check whether the considerations that went into questionnaire construction were sensible, obtaining feedback from a small sample of potential responders or, more extensive, pre-tests are encouraged (Frary 1996).

Questionnaires are essentially self-reports and not direct measurements of opinions; this of course bears the danger of deviations from ‘the truth’ (Martin 1996: 22p). For closed questions there is the danger of so-called “response sets” (Montello and Sutton: 2006: 86). However, in our case the subject of the questionnaire is not delicate in an emotional, social, legal or psychological sense, so this should be less of a problem.

Regarding privacy and ethics the American Psychological Association issued the *Ethical Principles of Psychologists and Code of Conduct* (APA 2002) which claims that scientist inform experiment participants before these give their informed consent about, for example:

- the purpose of the research, expected duration, and procedures
- reasonably foreseeable factors that may be expected to influence their willingness to participate such as potential risks, discomfort, or adverse effects
- any prospective research benefits
- limits of confidentiality
- incentives for participation
- whom to contact for questions about the research and research participants' rights

6.3 Methodology

6.3.1 Valley side slope characterisation

Operationalisation. The valley characterisation which the subsequent operationalisation relies on is the same as in the first case study (Section 4.3.2; see also Section 3.4.2). In that, the characterising properties of valleys were found to be the following:

- valleys are low areas or depressions relative to their surroundings.
- elongate
- (gently) sloping
- valleys often contain a stream or river

All of these are more or less implicitly already contained within our valley floor delineation algorithm. This is not surprising as we assumed that landforms may be approximated by their conceptual core (e.g. mountain by summit, valley floor by thalweg, valley by valley floor; see *Operationalisation* in Section 4.3.2). However, a way has to be found to 'spread' the (here: crisp) conceptual core in order to grasp the concept of the landform in question. Here, this means extending the crisp valley floor delineation to characterise valleys. Regarding the vague nature of the term *valley* this can be done only fuzzily in order to be sensible. In the field of topographic eminences such as mountains the whole characterisation process is often done crisply, i.e. the characterisation is a *delineation*. This applies, for example, for the method of *inverse watersheds* (see Section 2.3.5, Greatbatch et al. 2007). However, using such a method or the inverse equivalent for valleys leaves us with mountains or valleys, respectively, everywhere. What is thus needed is a method to give a fuzzy account of how valley-like any location within a drainage sub-basin is.

However, formal definitions (see Section 4.3.2 and the resulting characteristics listed above) do give us few and rather vague clues to what a valley actually may be. Most importantly, valleys are depressions, i.e. they are concave features while topographic eminences are characterised as convexities. Additional to this, it is deemed suitable to look at naïve connotations of the term *valley* or the expression *being in a valley* in order to shed light on the concept. This may be necessary (though dependent upon application) for more common terms which are often used in natural language and not only exclusively amongst scholarly people like geomorphologists. Other examples of such concepts which may benefit from naïve characterisations are *mountain*, *ridge* or *hill*.

Interestingly, in many Central European languages the prepositions used in connection with both *valley* and *mountain* (i.e. topographic depressions and eminences) are equivalent:

English:	"being in a valley"	"being on a mountain"
German:	"in einem Tal sein"	"auf einem Berg sein"
French:	"être dans une vallée"	"être sur une montagne"
Italian:	"essere in una valle"	"essere su una montagna"
Spanish:	"estar en un valle"	"estar en una montaña"
Portuguese:	"estar em um vale"	"estar em uma montanha"
Dutch:	"worden in een vallei"	"worden op een berg"

Referring to valleys, one is usually "in" one, referring to mountains one is usually "on" one (with exceptions for Spanish and Portuguese). As seen near the beginning of this section valleys are depressions or concavities. It seems, that through the preposition "in" being in a valley evokes a sense of *containment*. We would thus argue that valleys have the affordance of feeling contained. Mountains on the other hand probably have the affordance of feeling exposed (together with all amenities which come along with this affordance, such as having a good view of the surrounding landscape).

The essence of concavity and containment and their inverse, convexity and exposure, was thus chosen as a starting point for the valley side slope characterisation algorithm. Consider the example valley cross-sections in Fig. 59. In Situation A, 1 is clearly in the valley, even located on the valley floor. Location 2, however, is most certainly not fully in the valley anymore but rather on the adjacent topographic eminence. In Situation B, 3 is certainly in the valley (on the thalweg). At location 4 (a convex break of slope) something significant happens. Immediately above 4 an observer cannot see the whole bottom of the valley anymore, his view being partly blocked. Above location 4 an observer very probably feels less contained in the valley than below 4. At location 5 again, the observer is rather on a topographic eminence than in a topographic depression. Situation C is even more complex. Here, again, location 6 is considered to be in the valley and location 7 is a crucial break of slope. Here, even more clearly than in situation B, above the break of slope (above 7) an observer has an obstructed view onto the valley floor and very probably feels less "in the valley". At location 8 there is a second profound concavity before the slope rises steeply to the drainage divide, where an observer again would feel more on a topographic eminence.

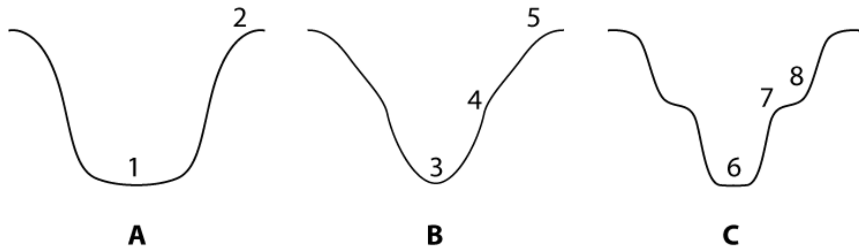


Fig. 59: Various valley cross-sections.

Additionally to an approach relying on convexity similar to the above reasoning, the possibility of using relative elevation per drainage sub-basin (patch) and the combination of the two approaches is explored. The second approach relies on relative elevation above the lowest point of the respective drainage sub-basin (patch); this means that valleyness continuously fades out with the observer moving up on the valley side slopes. It is hoped that an elevation-based approach may be sensible in situations similar to A with a more pronouncedly concave profile up almost to the drainage divide. There, a purely convexity-based approach would assign locations next to the drainage divide a still exceptionally high value of valleyness, which is clearly not realistic.

Algorithm. With regard to the data this case study relies on the same pre-processing as the first case study (Section 4.3).

In this case study, using a raster of drainage sub-basins, the distance of each non-valley floor pixel to the closest valley floor pixel of the same drainage basin was computed. The algorithm employed did not rely on the eight neighbour environment but calculated straight line distance between the two.

As the valley floor delineation the valley side slope algorithm is initially based on drainage sub-basins but divides these into their stream-separated parts, in order to be able to deal with opposing valley side slopes separately. This is because it was hoped to achieve better results under certain circumstances such as morphologically very different valley sides.

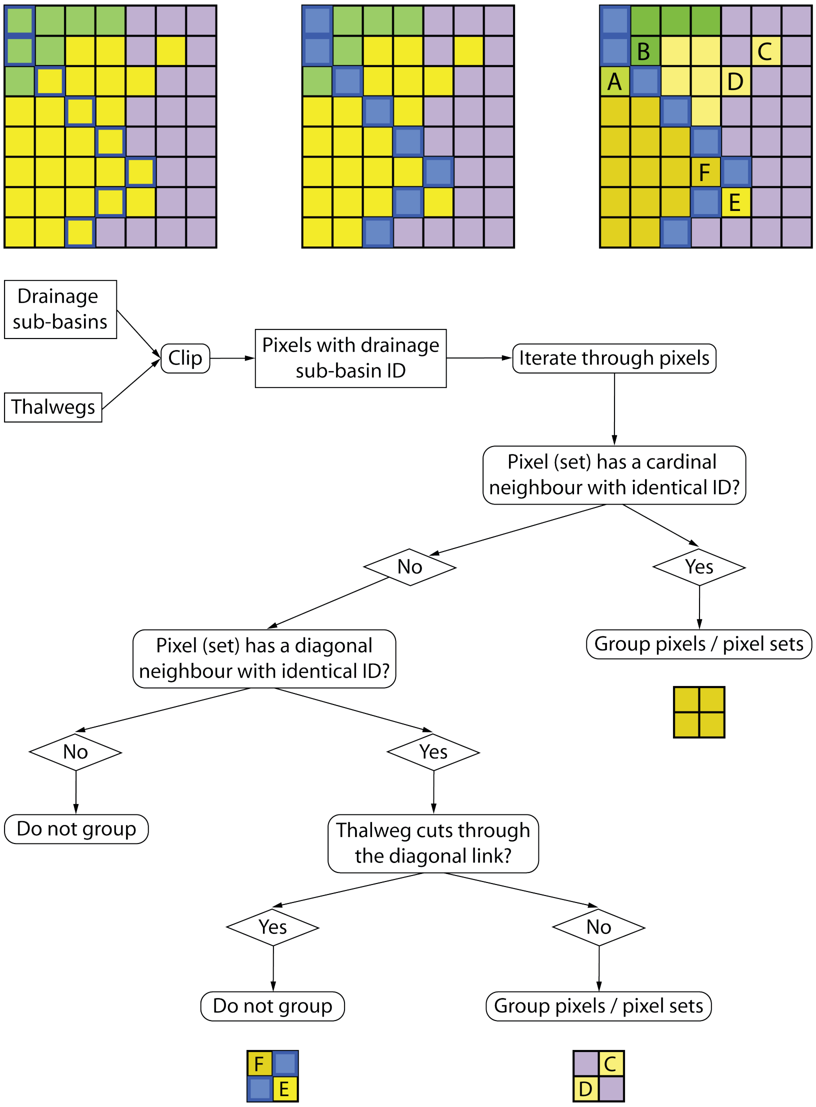


Fig. 60: Splitting of drainage sub-basins into distinct patches. The flow-chart details the processing; refer to text for comprehensive description of the algorithm's working.

Consider the top of Fig. 60 as an example. First, drainage sub-basins (except for headwaters) are split into parts through overlaying them with the raster of thalwegs (left). All drainage sub-basin cells falling on a thalweg are set to *NoData* (centre). An algorithm then assembles cells into drainage sub-basin parts by looking for cells which are 4-connected, i.e. which share a drainage sub-basin ID with one of their cardinal neighbours. Additionally, diagonal neighbours are inspected. If a cell happens to have a diagonal neighbour with identical drainage sub-basin ID, the configuration of the two cells is subjected to closer examination. Using the raster of drainage sub-basins with clipped thalwegs and a raster of flow directions the algorithm checks whether two diagonally adjacent cells are separated by a thalweg or not (right). If they are separated by a thalweg the two cells are regarded as belonging to two distinct drainage sub-basin patches (cell A and cell group B, cell E and cell group F in Fig. 60). If the two diagonally adjacent cells are not separated by an intervening thalweg, they are classified as belonging to the same drainage sub-basin patch (cell C and cell group D). Note that the procedure classifies cell E as belonging to a different drainage sub-basin patch (its own in this example) than the up- or downstream cell group {C, D}, although, orographically, the two parts are on the same side of the thalweg.

Subsequently, for the convexity-based approach it was tried to mimic the reasoning applied to Fig. 59. Starting from the valley floor, cells in each drainage sub-basin part are binned according to their distance to the closest valley floor cell in the same drainage sub-basin part. Binning distance was chosen as 1.5 cell distance. Due to the fact that the D8 flow algorithm was used in the derivation of flow directions, channel network and, eventually, drainage (sub-)basins, there are D8 typical artefacts present in the hydrologic data. Thus, there are situations where drainage sub-basins have one cell wide diagonally running parts (i.e. parts with a steady increase in cell distance from valley floor of $2^{1/2} \approx 1.414$). In such situations the adoption of 1.5 cell distance for binning prevents the occurrence of empty distance bins. This in turn helps avoid any further arbitrary decision as to how to deal with such empty bins which at the same time affect also their two neighbouring distance bins in the curvature calculation step described below.

Starting from the valley floor a curvature measure, c_i, is calculated for every distance bin i according to:

$$c_i = (elev_{i+1} - elev_i) - (elev_i - elev_{i-1}) \tag{12}$$

where $elev_{i-1}$, $elev_i$, $elev_{i+1}$ denote the mean elevation of the respective distance bin.

After the initial curvature computation each bin is revisited and the curvature value examined and treated according to the case differentiation (equation 13). Concave distance bins are disregarded, their curvature values are set to zero. Convex distance bins signifying convex breaks of slope as in Fig. 59 have their curvature values inverted in order to obtain positive values which facilitate the following calculations:

$$c_i = \begin{cases} > 0: & i \text{ is concave} \Rightarrow \quad c_i := 0 \\ = 0: & i \text{ is planar} \\ < 0: & i \text{ is convex} \Rightarrow \quad c_i := -c_i \end{cases} \tag{13}$$

The remapped curvature (or now: convexity) values are then multiplicatively weighted by the number of pixels, n_i, in the respective distance bin in order to obtain weighted convexity values:

$$c_{i,weighted} = n_i \cdot c_i \tag{14}$$

Weighted convexity values are then summed up over the whole of the drainage sub-basin (patch) to yield total convexity for that drainage sub-basin (patch):

$$C = \sum_{i=0}^{m} c_{i,weighted} \tag{15}$$

Then each distance bin is revisited and assigned a valleyness value which is computed based on the cumulative convexity outward from the valley floor to that very distance bin and the total convexity (15) encountered in the respective drainage sub-basin part. These two are combined in a division which varies from 0 (no cumulative convexity) to 1 (cumulative convexity equal to total convexity). Through a simple inversion via subtraction from 1 these values are redefined to a measure for the member cells of distance bin j we term convexity-based valleyness, $v_{c,j}$:

$$v_{c,j} = 1 - \frac{\sum_{i=0}^{j} c_{i,weighted}}{\sum_{i=0}^{m} c_{i,weighted}} = 1 - \frac{\sum_{i=0}^{j} c_{i,weighted}}{C} \in [0,1] \tag{16}$$

This procedure assumes that any convexity met when going from the valley floor outward to the drainage divides, diminishes the degree of being in a valley and increases the degree to which an observer may feel standing on a topographic eminence. In nature, in most valleys there will be a convex break of slope close to the drainage divide. Thus, valleyness will in most cases be above 0 up to the drainage divide. For valleys with relatively straight slopes the same will apply. Here, owing to the simplicity of the algorithm, potential minor midslope undulations on the valley sides may have a relatively large impact on the computed valleyness. The formulation as above also implies that valleyness always either stays constant or diminishes as one moves away from the valley floor; going outward valleyness will never increase.

The second, much simpler approach based on relative elevations computes valleyness as inverse relative elevation per drainage sub-basin (patch):

$$v_{e,j} = 1 - \frac{elev_j - elev_{min}}{elev_{max} - elev_{min}} \in [0, 1] \quad (17)$$

The combination of the two approaches can be done by simply computing the mean of the two measures (equations 16, 17) for each cell *j*:

$$v_j = \text{mean}(v_{c,j}, v_{e,j}) \in [0, 1] \quad (18)$$

6.3.2 Human subject experiment

We devise a human subject experiment to assess the valleyness estimation methods in the previous section. This is done with respect to the considerations which apply to questionnaire design (see Section 6.2.2) in mind.

Stimuli choice. Photographs taken by several colleagues at the Department of Geography of the University of Zurich were used as stimuli. First, a set of 6,251 photographs were considered which all contained a *geotag* in their EXIF data (Exchangeable Image File Format; EXIF 2007, MWG 2009), designating the approximate location of the camera/photographer when the photograph was taken. These positions had been acquired using a GPS logger and were matched with the photographs using the respective timestamps. Using the picture managing software *Picasa* (2009) the locations of all geotagged photos were exported into a Keyhole Markup Language (KML) file and then converted into a GIS-compatible comma separated file. Some ten entries have been deleted, since their location was saved as references to entries in Geonames.org (e.g. 'Geonames near: Zurich') rather than latitude and longitude coordinates. This process yielded 6,123 georeferenced image records – 5,503 records after exclusion of photographs which were not within the extent of the study area (e.g. in the Netherlands, in Germany, Austria, Italy and Greece).

A stratified sampling scheme was tested for reducing the number of image points based on the valleyness value of each image position. However, through the often clustered occurrence of photo locations (e.g. along a hiking trail or in a town) stratified random sampling of the points resulted in many points being very close together. Thus, the stratified random sampling scheme was discarded for a spatial one. Using a Java programme a photo location was chosen randomly. Then all photo locations closer to this point than a certain distance threshold were excluded from further sampling. The above two steps were iteratively repeated until the algorithm ran out of points for sampling or until a number of 200 photo locations has been obtained. This number of photos could be achieved by using a minimum separation distance of 3.5 kilometres. In order to obtain a final selection of 100 photos for the human subject experiment, the 200 photos were further sub-sampled. A first step in the additional sub-sampling was intentionally manual. This step served the purpose of getting rid of photographs which would not be suitable for the experiment regarding valleyness estimation. The *a priori* established rule base for this process considered the following cases to be excluded from the stimuli collection:

Case 1 Close-up photographs (of objects)

Case 2 Pictures within dense atmosphere which hinders sight considerably (e.g. in the middle of a forest or in dense fog)

Case 3 Pictures with mainly built-structures (e.g. pictures in settlements) without much clue regarding the topographic surroundings

The author of this thesis manually excluded photographs from the stimuli collection when he deemed they fall within one of the above categories. The advisor to the author acted as a second operator looking at both tentatively discarded and kept photographs, overruling some of the decisions and thereby further ensuring objectivity. This process eventually discarded 55 out of 200 photographs (see examples in Figs. 61 through 63) and thus kept 145 photographs in the tentative stimuli collection. The sub-sampling from 145 to the final 100 photographs was subsequently done in random manner.

The remaining 100 photographs were randomly allocated into four groups of photographs (so-called question-groups). The obtained distribution into four groups was slightly uneven, i.e. question groups did not contain 25 photographs each. This was remedied through a manual, but essentially random process which re-assigned group affiliations for some records, unaware of the location or the valleyness value of these records. The location of the 100 stimuli in geographic space can be seen in Fig. 64.

Fig. 61: Examples of excluded close-up photographs (case 1).

Fig. 62: Examples of excluded dense-atmosphere photographs (case 2).

Fig. 63: Examples of excluded built-structures photographs (case 3).

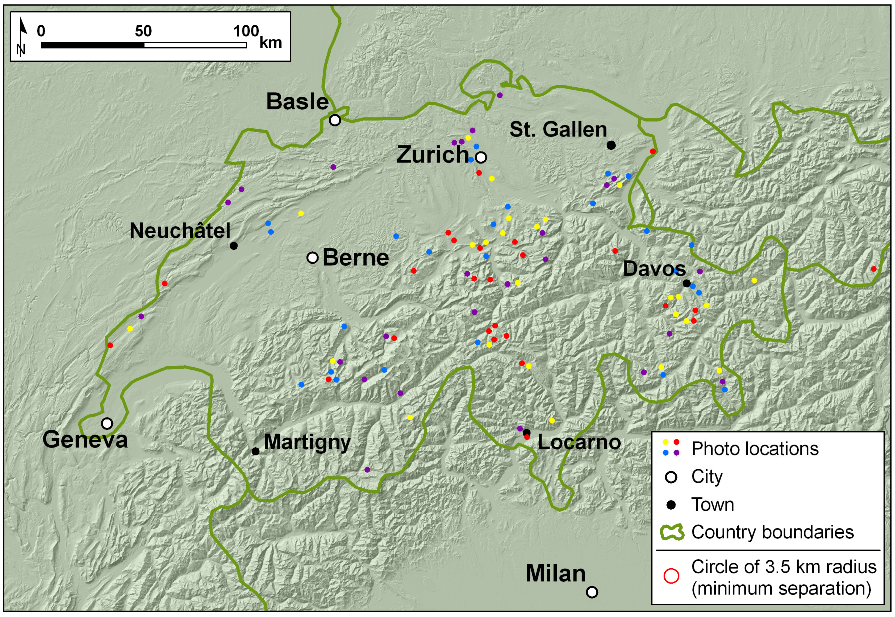


Fig. 64: Distribution of 100 remaining photo locations after manual pruning and further random sub-sampling. The four colours of photo locations represent their affiliation to one of the four question groups.

Questionnaire implementation. The questionnaires (one in German, one in English) were implemented as simple PHP (2009) websites using a template from earlier questionnaire surveys in, for instance, the TRIPOD project (TRIPOD 2009; see Appendix D for the PHP code).

Every participant could choose between the English and the German questionnaire and was randomly allocated to one of the four question groups. The display order of the stimuli of the respective question group was randomly shuffled for every participant in order to prevent order and context effects (see Section 6.2.2). Questionnaire participants could click their way through the individual questions within a single HTML document. The information regarding stimuli as well as the questionnaire results were stored in a MySQL database. The structure of the database tables can be seen in Appendix D. Upon completion of the questionnaire, a PHP document saved the questionnaire contents into the database and displayed a confirmation website to the participant. The questionnaire was extensively tested on Firefox, Internet Explorer, Opera and Safari browsers.

Fig. 65 shows an example question and stimulus image as it is displayed in the participant's browser. In the lower part is the question phrasing and the Likert scale which the participants had to use to answer the questions. Larger and additional depictions of the questionnaire's contents along with the full text of the introductory section can be found in Appendix E.

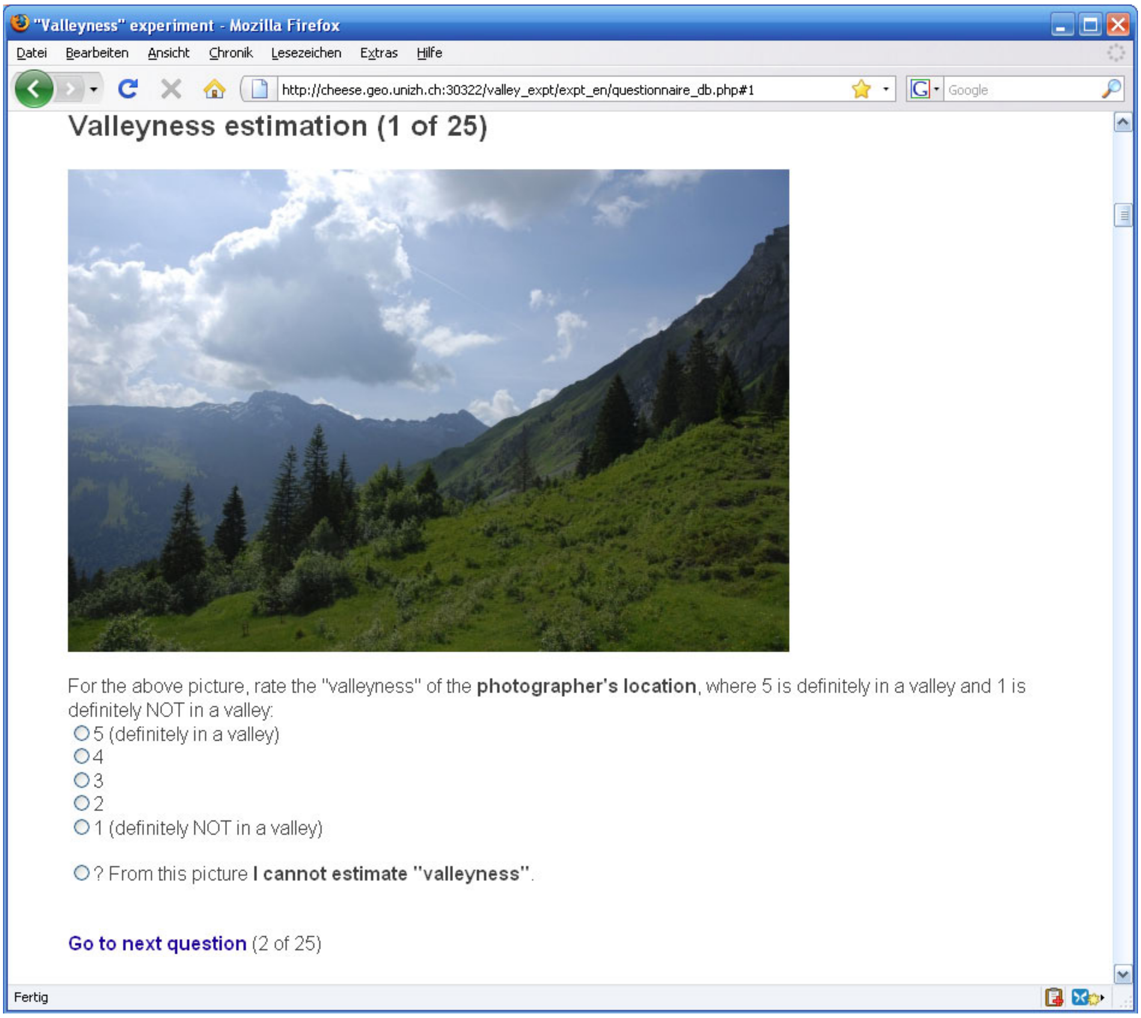


Fig. 65: Example of a "valleyness" question with stimulus image in the English questionnaire.

Participant sampling. The participants were recruited in three different ways. A mass e-mailing was sent to 8,751 members of the university who have given their consent to receiving such communication via the Legal Service of the University of Zurich. A second way of recruiting was e-mailing the questionnaire invitation to 150 members of the Geomorphometry mailing list (Geomorphometry 2009). Nearly a third of these addresses returned a delivery error, however. This e-mailing targeted a much more specialised audience (researchers interested in geomorphometry) the inclusion of which opens the opportunity of comparing the answers from different audiences. Lastly, an invitation to participate in the survey was sent out to friends, relatives and acquaintances of the author.

Within a few weeks 810 people have answered the request and participated in the survey.

Statistical analysis. A PhpMyAdmin (2009) web front-end to the database allowed for easy export of database records as comma delimited text files. For a specific analysis a complex SQL statement had to be devised in PhpMyAdmin in order to transform the questionnaire results table from a *one participant-one record* basis (comprising over 800 records) to a *one stimulus-one record* basis (comprising 100 records, one for each stimulus image). This is effectively a simultaneous transposition and aggregation of the results table which originally featured images as fields. The resulting data files where subsequently imported into Microsoft Excel, SPSS and R for further statistical examination.

6.4 Results and discussion

This section starts with a short description of some key overview statistics regarding the population of participants. In several following sections more sophisticated statistical analyses with regard to the questionnaire items (valleyness estimations) will be given.

6.4.1 Results of valleyness computations

This section shows some of the results of the valleyness computation[4] using equations (16), (17) and (18). Fig. 66 and 67 show the convexity-based and elevation-based valleyness, v_c and v_e, according to equations (16) and (17), respectively. Fig. 68 shows the combined valleyness v obtained through averaging v_c and v_e (equation 18). Through the influence of v_e the floor of the Rhine fault and the Po plain exhibit a non-uniform valleyness. Theoretically, this drawback could be amended by introducing a lower threshold of vertical relief within a drainage sub-basin below which v_e is weighted much less or not at all in comparison the v_c. Fig. 69 shows a simpler approach which used convexity-based valleyness v_c, wherever it was larger than v_e, and combined valleyness v elsewhere. Fig. 70, lastly, shows a close-up depiction of combined valleyness, v_c, in the area around Gürbe valley. More (though smaller) close-up depictions of valleyness can be seen in Figs. 78 and 79 (pages 199, 200) which depict outliers of regressions between algorithmic valleyness and valleyness estimates from the questionnaire.

[4] The displayed rasters have been moderately filtered using a low-pass (mean) filter in a circular neighbourhood with a 3 cells radius. This method has been adopted since the valleyness computation based on drainage sub-basins or sub-basin patches naturally exhibits more or less abrupt boundaries at drainage divides. The resulting rasters all still have a correlation with the original unfiltered ones of > 0.96, however. In the statistical analyses starting in Section 6.4.3 the raw rasters were employed.

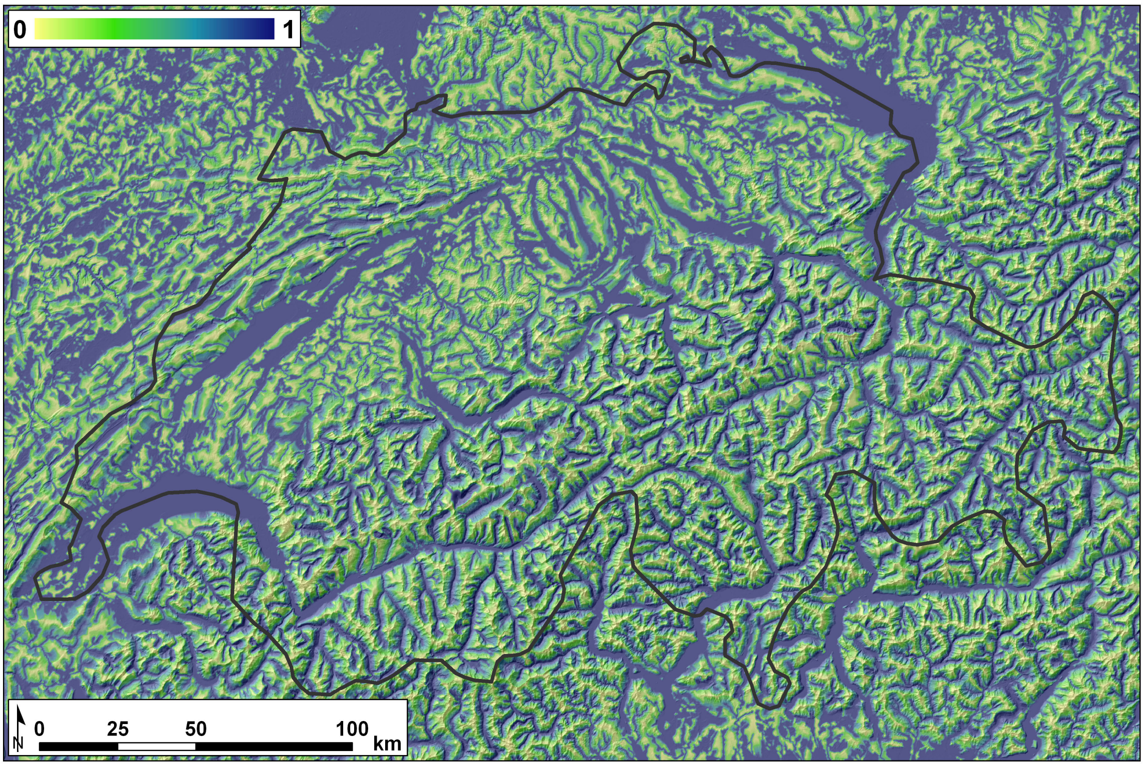


Fig. 66: Convexity-based valleyness, v_c, computed on drainage sub-basins, filtered, semi-transparent over hillshaded DEM. Black outline represents the border of Switzerland.

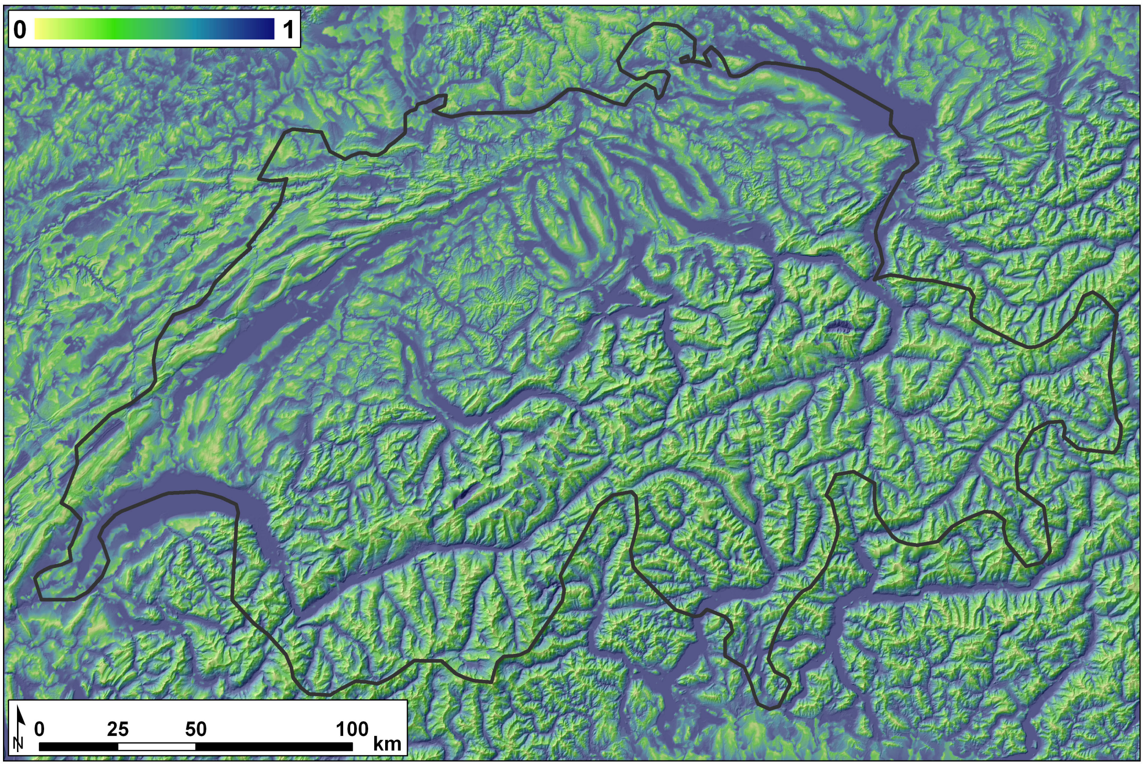


Fig. 67: Elevation-based valleyness, v_e, computed on drainage sub-basins, filtered, semi-transparent over hillshaded DEM. Black outline represents the border of Switzerland.

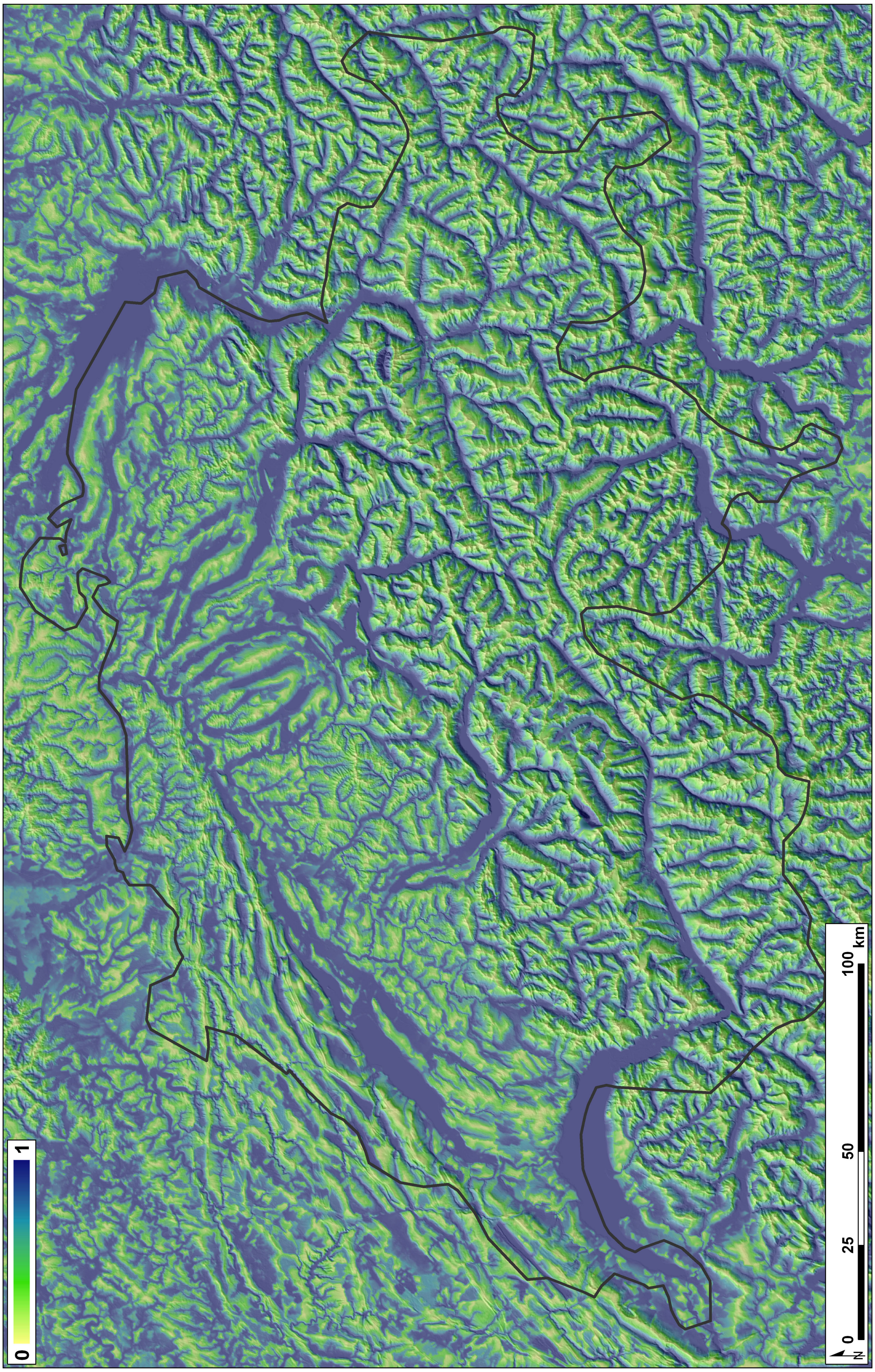


Fig. 68: Combined valleyness, *v*, computed on drainage sub-basins, filtered, semi-transparent over hillshaded DEM. Black outline represents the border of Switzerland.

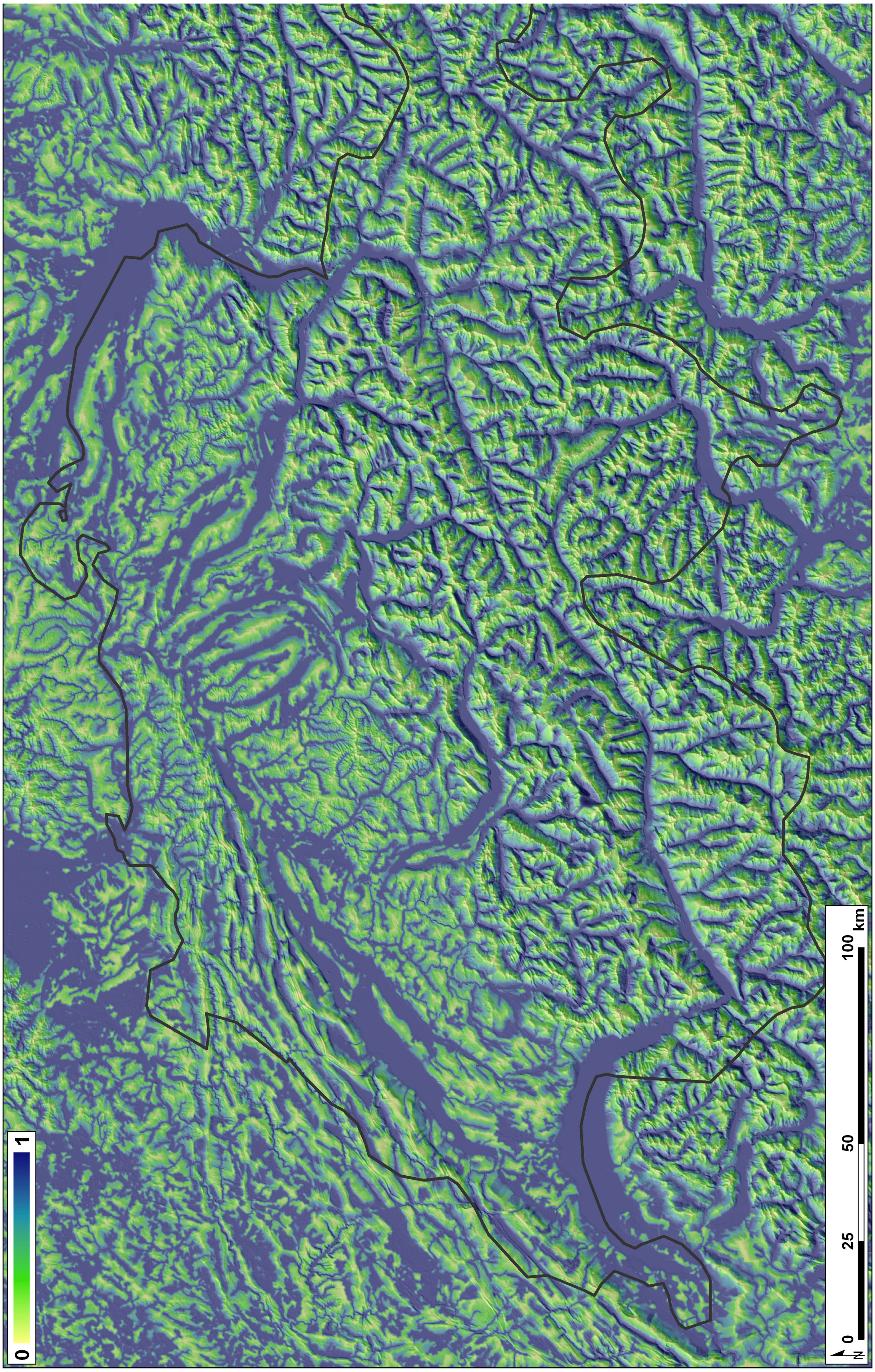


Fig. 69: Combined valleyness with emphasis on valley floors, computed on drainage sub-basins, filtered, semi-transparent over hillshaded DEM. Black outline represents the border of Switzerland.

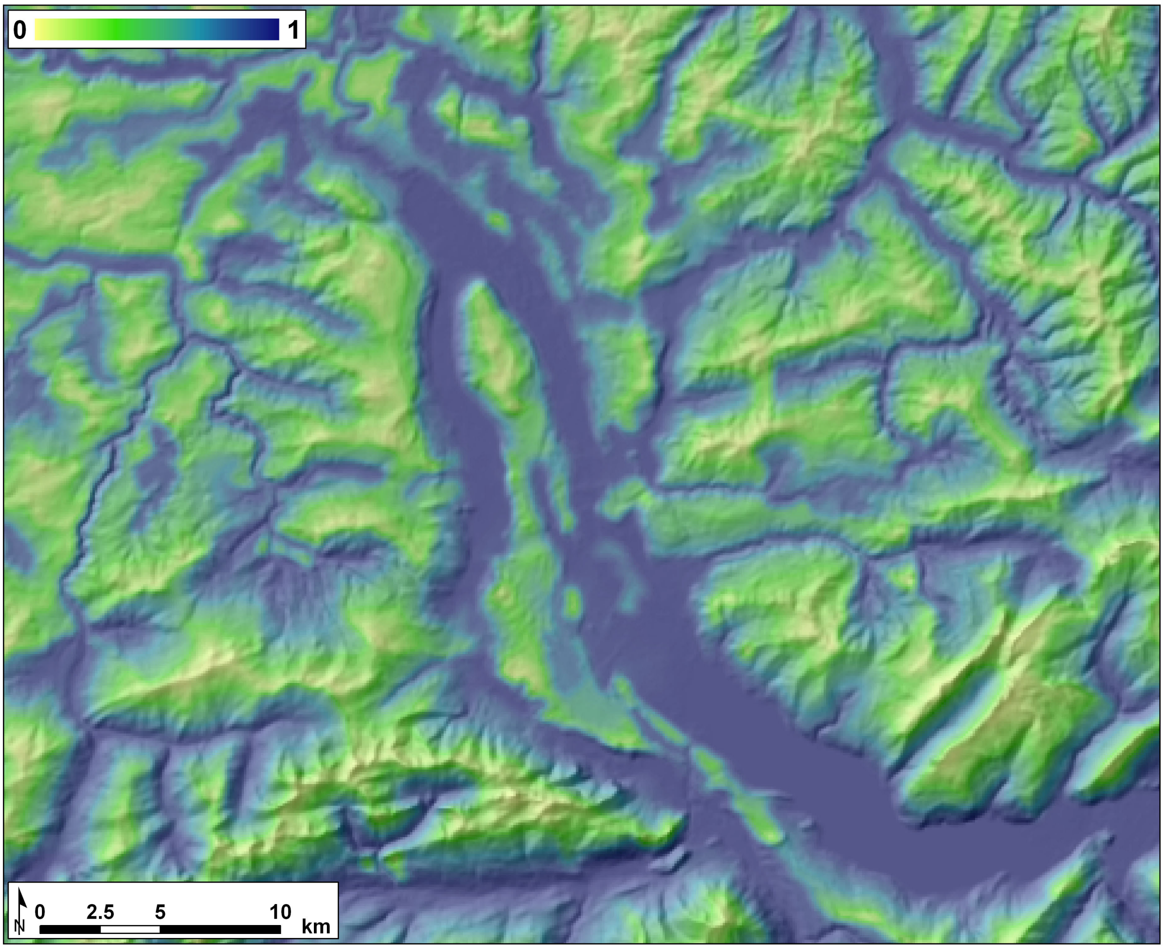


Fig. 70: Combined valleyness, *v*, computed on drainage sub-basins,
filtered, semi-transparent over hillshaded DEM.

6.4.2 Composition of the group of questionnaire participants

Demographic composition. A total number of 810 people answered the questionnaire. As can be seen from Fig. 71 the majority of people regarded themselves as laypersons ($n = 651$). To distinguish laypersons from students ($n = 70$) and researchers ($n = 47$) in the geosciences the participants were offered a choice between the following three options:

- I am a researcher in the field of geosciences (e.g. geography, geomorphology, geomorphometry, ...)
- I am a student in the field of geosciences (e.g. geography, geomorphology, geomorphometry, ...)
- I am neither of the above

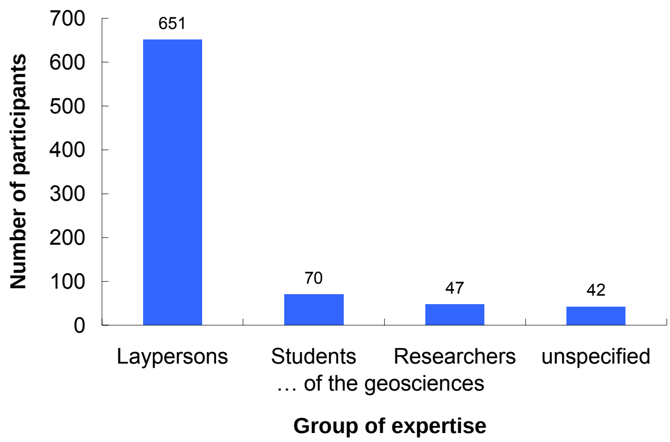


Fig. 71: Distribution of participants into groups of expertise.

42 persons (5.19 %) did not answer the question regarding their expertise at all. Judging the language distribution in this group (Fig. 72, left), it fits nicely between laypersons and students of the geosciences. So the group is likely mostly made up of (student) laypersons. Nonetheless this group was excluded from the analysis which involved stratifications according to groups of expertise.

Among those people who specified their expertise there was a significant difference regarding languages. While almost 47% of the researchers answered the English questionnaire, that proportion was, as expected, much lower among laypersons and students. In conjunction with the above statistics regarding expertise classes this means that the proportion of German questionnaires is much higher than that of English questionnaires (95.8% versus 4.2%). Subsequent statistical analysis will investigate whether there are statistically significant differences in the valleyness estimates by researchers (and possibly students) in the geosciences and laypersons.

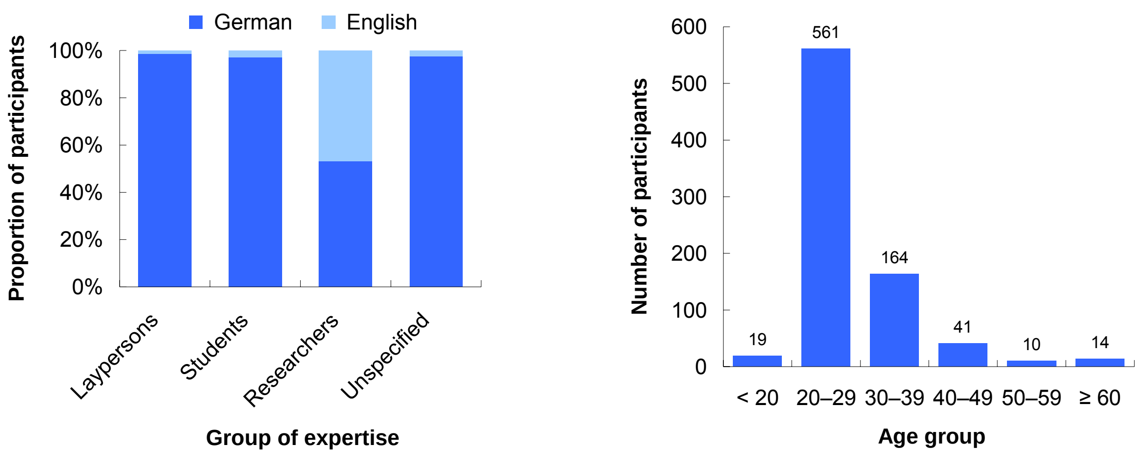


Fig. 72: Language (left) and age distributions of participants (right).

The distribution of the participants' age (Fig. 72, right) is unequal for the same reason which shapes the language distribution (prevalence of students); it experiences a large positive (right) skewness with a peak in the *20–29 years* class which most students belong to.

Overall, the sample is thus biased towards German-speaking, young laypersons, i.e. mainly towards students from the university mailing list, from other departments than Geography and towards other laypersons outside university.

As a result of the random allocation of individual participants, the distribution of participants into the four different question groups is relatively equal (193, 211, 218, 188 participants, respectively). Nevertheless, the statistical examinations employing near-raw data will use relative rather than absolute numbers, in order not to compromise the statistics through the unequal number of participants in the four question groups.

Spatial composition. The questionnaire asked participants for their places of residence. The global and European distributions of questionnaire participants can be seen in Appendix E. Generally, there was a strong bias towards Europe and within Europe towards Switzerland (apart from Switzerland, significant participation took place from Germany with 15 and from the Netherlands with 8 participants). The distribution within Switzerland is presented as a density surface in Fig. 73, reflecting the catchment area of the University of Zurich.

Several participants did not declare their place of residence or – in the case of Switzerland – resorted to declaring the first order administrative division (canton) rather than a specific city or town. Although, for example, 'ZH' for the canton of Zurich is also used as an abbreviation for the city of Zurich, inclusion of such records into the spatial datasets depicted in Fig. 73 (and in Appendix E) was avoided. Also, possibly ambiguous entries were excluded. Thus the analysis was done on 771 participants' locations. The geocoding of the textual locations was done using an online service (Holmstrand 2009) which uses the Yahoo! Geocoding API. This approach was found to yield sufficiently exact results for this application.

From Fig. 73 it can be clearly seen that the agglomeration and city of Zurich is very heavily represented along with some of the other large cities of Switzerland such as St. Gallen, Lucerne, Schaffhausen, Basle, Berne and Lugano. While most of the participants could be attributed to what is termed *Mittelland* (i.e. the flatter, more populated and crescent-shaped part of Switzerland), there are also contributions from more mountainous places close to or within the Alps. Note though that the potential migratory history of participants (within Switzerland or abroad) is not elicited in the questionnaire. The spatial distribution within Switzerland is a result of the factors population distribution (favours larger cities), the university-internal mass mailing (favours agglomeration of Zurich, larger nearby cities without a university such as Lucerne, Winterthur and Schaffhausen) and the addressing of friends and families (favours the regions of St. Gallen, Zurich and Berne).

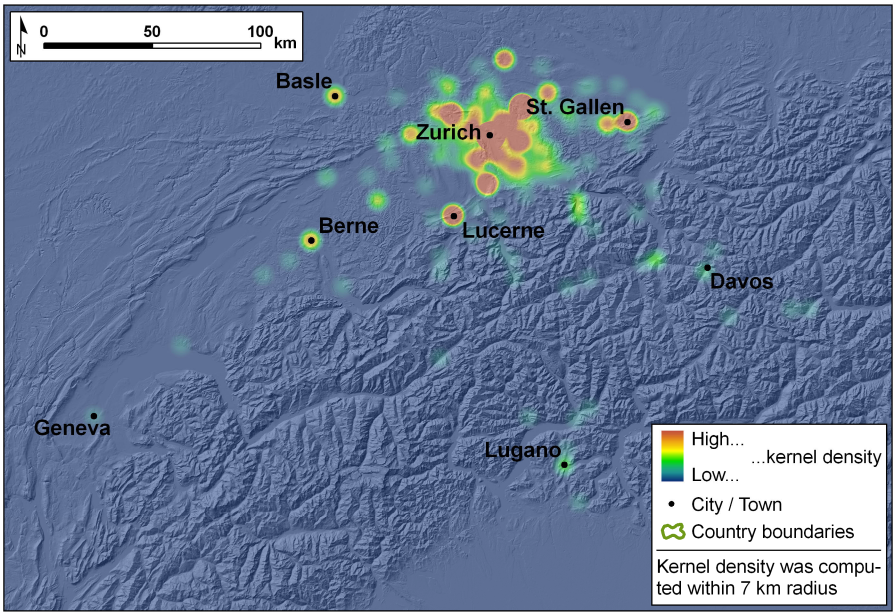


Fig. 73: Kernel density of participants' places of residence in Switzerland.

Questionnaire completion time. The online questionnaire had a feature to track and record the time participants spent to answer the questionnaire (more precisely: time span from loading the page initially to pressing the submit button). The median of this time span was 5.7 minutes, the mean 13.1 minutes and the standard deviation 145.9 minutes. However, excluding one outlier of almost 70 hours brings the mean down to 8 minutes and the standard deviation to 11.3 minutes. 15 participants completed the questionnaire in less than 2 minutes. However, only one of those persons filled in answers to the stimulus questions. Although feasible, no records were excluded based on the time for completion, also because defining a threshold value for a 'valid participation' would be completely arbitrary.

6.4.3 Comparison of expertise groups and statistics of valleyness

Assumptions. Having obtained the results of the questionnaire experiment from the database in a *one stimulus-one record* basis (comprising 100 records), one should beware of assumptions. Firstly, one cannot assume that the four question groups are equivalent with respect to the distribution of the answers. There could be an influence which led participants in one question group to answer the questions significantly differently than those in another question group. Secondly, one cannot assume that the three expertise groups – laypersons, students and researchers – answered the questions equally, even within the same question group.

Thus, firstly, the existence of differences between question groups and expertise groups are tested. A scheme is adopted which first tests for differences across the question groups, stratified according to expertise groups. If there are no such differences the four question groups can be aggregated within every expertise group. This leads to a larger size of samples and thus to a more valid result in the subsequent testing for differences among the answers by different expertise groups.

Considerations for testing question group effects within expertise groups. There are several ways of analysing the questionnaire data. It is clearly valid to look at the counting variables corresponding to the items in the Likert scale of the questionnaire (V_1 (definitely not in a valley), V_2, V_3, V_4, V_5 (definitely in a valley) and V_{99} ("from this picture I cannot estimate valleyness")). In order to make these counting variables comparable across different question groups (with only approximately equal number of participants), the relative amounts of answers were computed using equation (19):

$$rV_i = \frac{V_i}{V_{99} + \sum_{j=1}^{5} V_j} \qquad \forall i : i \in \{1, 2, ..., 5, 99\} \qquad (19)$$

Table 6: Example dataset of counting variables.

ID	V1	V2	...
1	10	5	
2	5	10	
3	5	0	

However, there is still a significant shortcoming when this approach is used to compare different subsets of the data. Looking at the (relative) counting variables one compares the distribution of each individual variable, without taking into account the distributions of neighbouring related counting variables. In Table 6 there are three example records. Comparing the three records column-wise, i.e. in a per-counting-variable pattern, looking at V_1

one would judge cases with IDs 2 and 3 to be equally similar to case 1. However, taking into account the neighbouring variable V_2, case 2 is clearly more similar to case 1 than case 3. Thus it was decided to use the relative counting variables only in the exploratory statistics, where they all can be displayed together, but not in the inference statistics comparing groups.

In order to take into account the interrelationships between the counting variables measures of centrality were used. These are stronger in comparing the distributions of participants' answers. Mean valleyness, v_{mean}, was computed:

$$v_{mean} = \frac{\sum_{i=1}^{5} V_i \cdot i}{\sum_{i=1}^{5} V_i} \tag{20}$$

and median valleyness, v_{median}:

$$v_{median} = median(\text{individual valleyness estimates}) \tag{21}$$

In both v_{mean} and v_{median} values of V_{99} were disregarded, since they cannot be sensibly placed on a numerical scale along with the other values. The averaging step in equation (20) implies that the level of measurement in the questionnaire is at least interval. This is a matter of debate for the Likert scale, but interval level is often assumed (Montello and Sutton 2006: 89). The question does not pose itself for v_{median}, since the median can be computed also on an ordinal scale.

Testing for normality. In order to determine a suitable set of statistical tests, tests for normality were carried out both for v_{mean} and v_{median}, adopting a confidence level of 95%. The results in Table 7 reflect the proportion of distributions of v_{mean} and v_{median} in a question group where the null hypothesis of normality was rejected. For every expertise group four question groups were assessed.

Table 7: Test for normality of v_{mean} and v_{median} in all question groups, stratified according to expertise.

	Proportion of rejection of null hypothesis (normality of sample)					
	Kolmogorov-Smirnov test			Shapiro-Wilk test		
Variable	Laypersons	Students	Researchers	Laypersons	Students	Researchers
v_{mean}	0%	0%	25%	25%	0%	0%
v_{median}	100%	75%	75%	100%	75%	75%

The results show that v_{mean} in question groups and expertise groups is dominantly normally distributed. Thus an approach employing a parametric test is legitimate for this variable. The distributions of v_{median} in question groups and expertise groups are mostly non-normal; this is due to the discrete nature of the median valleyness. Thus only non-parametric tests are legitimate for this variable. Consequently, a two-fold analysis of the samples across question groups was adopted. Firstly, the question groups are compared using a combination of non-parametric tests on v_{median}. Secondly, a parametric test (one-way analysis of variance) is carried out on the predominantly normally distributed aggregate variable v_{mean}.

Testing for question group effects within expertise groups. The results of two non-parametric tests (Kruskal-Wallis H test and median test) in Table 8 imply that the median valleyness values of different question groups within the same expertise group likely stem from the identical population and have equal medians, respectively.

Table 8: Test statistics on the median valleyness, v_{median}, across question groups, stratified according to expertise.

p-values					
Kruskal-Wallis H test			Median test		
Laypersons	Students	Researchers	Laypersons	Students	Researchers
.221	.237	.276	.211	.104	.244

The second derived measure, v_{mean}, was subjected to a one-way analysis of variance (one-way ANOVA). ANOVA could in no case reject the null hypothesis of equal means of v_{mean} among question groups in the three expertise groups (Table 9).

Table 9: Test statistics on the mean valleyness, v_{mean}, across question groups, stratified according to expertise.

p-values		
One-way ANOVA		
Laypersons	Students	Researchers
.406	.190	.302

Due to these consistent results it is legitimate to aggregate the individual question groups per expertise group in three individual (one per expertise group) datasets for the subsequent investigations of potential differences between expertise groups.

Exploratory analyses of aggregated datasets. Using the three aggregated datasets, some exploratory analyses were conducted. As can be seen both from Table 10 and the boxplots in Fig. 74, the distributions of the relative counting variables (proportion of answers V_1 through V_5 and V_{99}) are different for different expertise groups. In all groups of expertise both looking at the mean and the median of proportions reveals a pattern of lower proportions for higher valleyness estimates (i.e. towards V_5). Lowest in all expertise groups is the proportion of V_{99} ("from this picture I cannot estimate valleyness"). This trend of falling means and medians is only very slightly broken for the mean in the group of laypersons (where mean(rV_3) < mean(rV_4)). The maximum values of all distributions do follow a similar, if in comparison more often broken, pattern. Clearly, all expertise groups show a tendency to have a higher mean and median proportion at the lower end of the valleyness spectrum, as well as higher maxima in this area. This does not necessarily mean that the sampled answers are biased (though they could be); it could be the case that overall there were more stimuli that evoked answers of low valleyness than there were such that evoked answers of high valleyness. Which one of these two considerations applies (or if both apply, which one applies to what degree) cannot be answered, since it would necessitate *a priori* what this study is after – some objective way of assessing the valleyness of a photographer's location.

Table 10: Descriptive statistics of the relative counting variables stratified according to expertise (Standard errors – Skewness: 0.241; Kurtosis: 0.478).

Expertise	Var.	Min	Median	Mean	Max	Std.dev.	Skewness	Kurtosis
Laypersons	rV_1	.01	.3136	.3426	.94	.23956	.738	−.172
	rV_2	.02	.2030	.2052	.41	.08505	.010	−.176
	rV_3	.00	.1472	.1451	.29	.07121	−.147	−.691
	rV_4	.00	.1287	.1477	.42	.10405	.669	−.379
	rV_5	.01	.0716	.1086	.66	.10783	2.285	7.418
	rV_{99}	.00	.0420	.0508	.25	.04423	1.593	3.554
Students	rV_1	.00	.2381	.3000	.95	.25825	1.071	.504
	rV_2	.00	.2308	.2249	.63	.13871	.547	−.008
	rV_3	.00	.1538	.1615	.50	.10931	.548	.115
	rV_4	.00	.1151	.1486	.56	.13050	.918	.532
	rV_5	.00	.0769	.1125	.57	.13203	1.488	2.035
	rV_{99}	.00	.0476	.0525	.38	.06757	1.850	5.123
Researchers	rV_1	.00	.2308	.2860	1.00	.26048	.989	.571
	rV_2	.00	.1818	.1955	.60	.14189	.597	−.212
	rV_3	.00	.1269	.1546	.70	.14550	1.250	1.838
	rV_4	.00	.1000	.1474	.64	.13706	1.035	.974
	rV_5	.00	.0769	.1355	.67	.17065	1.228	.515
	rV_{99}	.00	.0769	.0810	.38	.09639	1.034	.167

Comparing the means for individual relative counting variables across expertise groups it seems that the researchers tend to have more estimates of high valleyness (near rV_5) and less estimates of low valleyness (near rV_1) than the students and especially the laypersons do. Interestingly, researchers also more often opted for V_{99} (“from this picture I cannot estimate valleyness”) than the other groups. However, the sample of researchers is with $n = 47$ relatively small and thus, a small absolute number of answers V_{99} have a considerable influence.

Both standard deviation and interquartile range do not show a simple systematic behaviour. If anything, both are highest at the lower and at the upper end of the spectrum of answers. Interestingly, from the kurtosis one can see that distributions of rV_5 and rV_{99} are clearly more peaked than those of the other variables in the groups of laypersons and students. In the group of researchers, however, the contrast between different distributions is much less and the most peaked values are those near the middle of the spectrum of answers, rV_3 and rV_4.

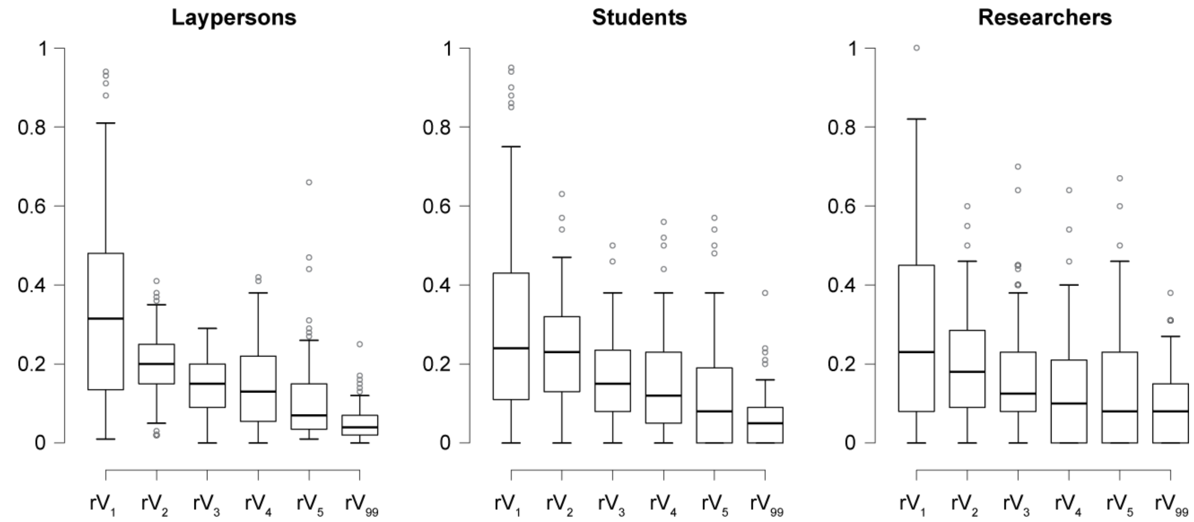


Fig. 74: Boxplots of relative counting variables per expertise group.
Outliers (°): 1.5–3 interquartile ranges (IQR) from median; extremes (*): > 3 IQR from median.

While the analysis of the relative counting variables, which are very close to the original raw data, may be revealing, it is also relatively complicated. It is thus accompanied by the analyses of the aggregated measures v_{mean} and v_{median}. Table 11 indeed shows the aggregated effects of some issues pointed out previously. Both the mean of v_{mean} and v_{median} increase with higher expertise. That means that overall the researchers estimated the photographer’s locations for the stimuli more “valley-like” than students and these in turn more than laypersons. Also, the maximum of v_{mean} is highest in researchers. Similarly, the standard deviations of both v_{mean} and v_{median} increase slightly with higher expertise. However, this could in fact be an indirect effect of the sizes of expertise groups.

Table 11: Descriptive statistics of v_{mean} and v_{median} stratified according to expertise (Standard errors – Skewness: 0.241; Kurtosis: 0.478).

Expertise	Var.	Min	Median	Mean	Max	Stddev.	Skewness	Kurtosis
Laypersons	v_{mean}	1.10	2.4176	2.4538	4.52	.74368	.307	−.292
	v_{median}	1	2	2.240	5	.9936	.468	−.524
Students	v_{mean}	1.05	2.4286	2.5269	4.38	.82420	.136	−.571
	v_{median}	1	2	2.450	5	1.0384	.419	−.555
Researchers	v_{mean}	1.00	2.6125	2.6179	4.60	.87800	.069	−.765
	v_{median}	1	2	2.495	5	1.1180	.328	−.881

The statistical data in Table 11 suggest that, while there are differences between expertise groups, they are most probably too weak to be statistically significant. The next section will describe the results of testing for differences between expertise groups.

Testing for normality. Test for normality of the aggregated measures in expertise groups yielded a similar picture to the tests which were carried out over the question groups earlier; while the null hypothesis of normality was rejected at the 95% confidence level for v_{median} throughout all groups of expertise, it could not be rejected for v_{mean}. Thus, again, for v_{median} Kruskal-Wallis H and median test were applied, while one-way ANOVA was applied with v_{mean}.

Testing for expertise group effects. Neither of the tests carried out on v_{median} could reject the null hypotheses of identical populations or equal medians at the 95% confidence level (Kruskal-Wallis H: $p = 0.231$; median test: $p = 0.217$). Regarding v_{mean}, one-way ANOVA at the 95% confidence level does neither reject the null hypothesis of equal means across groups of expertise ($p = 0.365$).

Hence, as expected, the statistical tests could not detect differences in the answers given by participants of different expertise groups. While some trends could be pointed out which varied systematically with the level of expertise, these differences are not statistically significant. Due to this result the data from different expertise groups can be aggregated for the further analyses.

6.4.4 Potential biases in valleyness estimation

This section will detail some potential confounding factors regarding the estimation of valleyness by questionnaire participants.

Definition of indicator variables. Looking at the questionnaire data and the stimuli it was hypothesised, that potentially there could be clues within the images leading participants to answer in a specific way. Thus, indicator variables were defined. These encompassed:

Indicator variable:	Levels:
Position of the horizon	below / above observer / at equal height
Vertical viewing direction	down / level / up
Relative horizontal viewing direction	into the valley (perpendicular to thalweg) / out of the valley / along the valley's principal direction
Presence of sky in the stimulus image	yes / no
Presence of snow in the stimulus image	yes / no
Presence of rock in the stimulus image	yes / no
General concavity of the image contents	yes / no
Presence of a potential plain	yes / no

The first three represent the orientation of the observer and his or her view. The materials (sky, snow, rock) were primarily covered with regard to Owens and Slaymaker (2004) and the findings of Derungs and Purves (2007). Those findings were related to topographic eminences of the mountain category; however, presumably the presence or absence of these materials could also influence the judgment of valleyness.

The indicator regarding *general concavity of the image contents* was dedicated to the general impression a person may experience being confronted with the stimulus. The question was: "Does the image rather portray convex things or concave things?"

The indicator regarding the *presence of a potential plain* was introduced into the analysis because it was noted in the exploratory analysis that participants' responses show significant scatter for some stimulus images showing vast low places for example near large prealpine lakes in Switzerland. The location associated with most of these stimuli was considered very valley-like by the algorithm. It was hypothesised that while some participants asserted they feel like being in a valley, others expressed doubts and would probably have opted for feeling like being in a low place, but that this place was too broad and/or had to low sideslopes to call it a valley. In other words, it was suspected that some stimuli did not confront participants with a potential dichotomy of *valley vs. non-valley* (or *valley vs. mountain*) – as had been hoped when setting up the questionnaire – but with a trichotomy *"lower and flatter than a valley" – valley – "higher and less flat than a valley"* (or *plain – valley – mountain*) (on this point see also e-mails 1 and 2 in Appendix G).

All indicator variables (in context of regression also known as dummy variables) were assessed for each of the stimuli by the author of this thesis. Thus, – depending upon the indicator variable assessed – there is a substantial amount of subjectivity involved.

Testing effects of indicator variables on valleyness estimates. To decide on appropriate statistical tests (parametric or non-parametric), the normality of v_{mean} and v_{median} was tested in all stratifications of the indicator variables. Regardless of the indicator variable used in the stratification, tests for normality of v_{mean} and v_{median} at the 95% confidence level were very uniform. The null hypothesis of normality was always accepted for v_{mean}, while it was rejected in all but one case for v_{median}. As a consequence, the comparisons of v_{mean} and v_{median} in different strata was again done using one-way ANOVA on the former and non-parametric tests on the latter.

v_{mean} showed significant differences when stratified according to either of *position of the horizon*, *vertical viewing direction* and *relative horizontal viewing direction* ($p < 0.001$). *Presence of sky*, *rock* and *snow* were relatively clearly dismissed of having an effect on v_{mean}; *snow* least clearly ($p = 0.986$, 0.431 and 0.212, respectively). The *general concavity of the image contents* and the *presence of a potential plain* had no significant impacts ($p = 0.341$ and 0.171, respectively), but the latter had a low *p*-value. The nonparametric tests on v_{median} yielded results which were consistent with these findings (Kruskal-Wallis H test with $p = 0.159$ and median test with $p = 0.346$).

Cross-tabulations reveal an especially strong relationship between *vertical viewing direction* and *relative horizontal viewing direction* (highly statistically significant measures of association ranging from 0.59 to 0.83 on a scale of [0, 1]). The relationships between *vertical viewing direction* and *relative horizontal viewing direction*, respectively, and *position of the horizon*, were considerably weaker (still highly statistically significant measures of association ranging from 0.32 to 0.45). Intuitively, one would indeed expect a relationship between the three variables. Given a photographer was looking towards the thalweg in a valley, the probability of looking down is high, too. Inversely, looking out of a valley usually means looking up. Clearly, the looking direction can also affect the position of the horizon. Now, because all these measures through a similar argument are also linked to the position of the observer within or along the edges of a valley, it cannot quite be known what the found effects mean. Clearly, within the setting of this experiment there is no way of knowing for sure, whether these parameters have affected the participants' valleyness estimates acting as a bias in the study or whether changes in the *vertical viewing direction* go together with changes in valleyness estimates because both are tied to a third variable, *namely the position in the valley*. In this latter case the *vertical viewing direction* would not act as a bias in the study, but is bound to vary more or less systematically with an underlying 'true' factor which we expect to affect valleyness estimates: the actual valleyness. It is also possible that there is in fact a mixture of the two influences; however, this cannot be assessed in the current study either. For that one would need to have photographs from the same position where above three variables vary.

6.4.5 Relation of valleyness estimates and valleyness measures

All-encompassing regression and correlation analysis. The *R* package *lmodel2* (CRAN 2009) was used to conduct reduced major axis regressions[5] between the stimulus statistics (comprising all groups of expertise and thus essentially all participants) and the valleyness measures (convexity-based valleyness, v_c, elevation based valleyness, v_e, and the mean combination of both, v) as derived by the algorithm presented in Section 6.3.1. Reduced major axis regression (RMA; Model II regression) was used rather than an ordinary least squares (OLS; Model I regression) solution, since in this case there is no clear definition of predictand and predictor, the latter of which is assumed to be error free in OLS regression. Rather two measures are compared without either being assumed to predict the other, to be calibrated against the other or to be error-free (Mark and Church 1977).

[5] The authors of the tool use the term *standard major axis* (SMA) rather than *reduced major axis* regression. More confusingly, the standard abbreviation of the latter (RMA) is used for *ranged major axis* regression in the context of *lmodel2* and accompanying documentation (cf. also Legendre and Legendre 1998: 510).

As an additional piece of information the uncertainty associated with the judgment of each stimulus shall be used in illustrations and analyses. The computation is partly based on the percentage of answers V_{99} ("from this picture I cannot estimate valleyness"):

$$rV_{99} = \frac{V_{99}}{V_{99} + \sum_{j=1}^{5} V_j} \tag{22}$$

Equation (22) is then combined with the standard deviation of individual valleyness estimates, v_{std}, (both normalised over all stimuli into [0, 1]) to yield preliminary uncertainty $ú$ (equation 23). While v_{std} characterises the dispersion in valleyness judgment (i.e. the ambiguity), rV_{99} is a direct representation of inability of judgment. Both can be understood as aspects of uncertainty. They are added rather than multiplied in order to prevent either one (being 0) annihilating $ú$ irrespective of the value of the other. $ú$ in turn was normalised onto [0, 1] using equation (24) (where $max_n = 1$, $min_n = 0$) to yield uncertainty u.

$$[0,2] \ni ú = \frac{rV_{99}}{\max\limits_{stimuli}(rV_{99})} + \frac{v_{std}}{\max\limits_{stimuli}(v_{std})} \tag{23}$$

$$u = (ú - \min_{stimuli}(ú)) \cdot \frac{max_n - min_n}{\max\limits_{stimuli}(ú) - \min\limits_{stimuli}(ú)} + min_n \tag{24}$$

Two exemplary RMA regressions from mean and median valleyness as derived from the questionnaire data on algorithmic combined valleyness measures can be seen in Fig. 75. The black lines indicate the regression lines, while the grey lines represent the 95% confidence intervals for the regression gradient. The scatterplot dots are coloured according to the associated uncertainty, u (equation 24). For clarity, in all subsequently displayed scatterplots u has been averaged for points whose coordinates shared three decimal places both on the x and the y axis (i.e. which almost or perfectly coincided).

As can be seen, there is considerable scatter in the data. However, there is a trend pattern in the scatterplots which shows that the regression though far from very clear is still substantiated. As a tendency (e.g. near the upper end of the algorithmically derived valleyness) the less certainly judged stimuli are often found near the fringes of the point cloud. However, there are also notable exceptions to this.

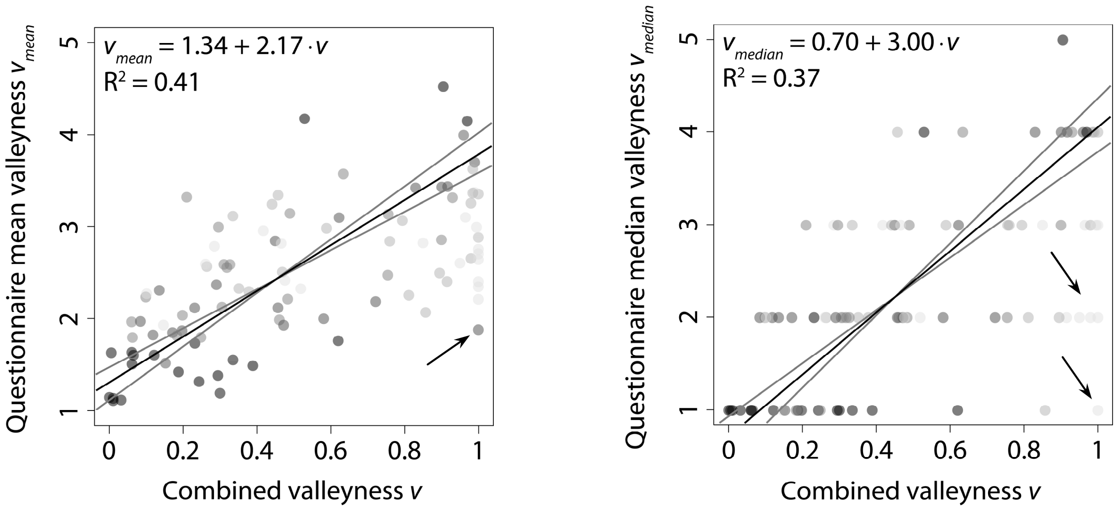


Fig. 75: RMA regression between algorithmically derived valleyness and v_{mean} (left) and v_{median} (right). Grey lines represent the 95% confidence intervals for the regression's gradient. The dots representing the stimuli are coloured according to the uncertainty of the valleyness estimates (five equal intervals); dark: low uncertainty, light: high uncertainty. The arrows mark areas of notable outliers of the regression.

Table 12: RMA regressions of v_{mean} and v_{median} on algorithmic valleyness measures.

Regression...	based on sub-basin patches		based on sub-basins	
	v_{mean}	v_{median}	v_{mean}	v_{median}
...versus convexity-based valleyness v_c				
Coefficient	1.92	2.66	1.91	2.64
Intercept	1.52	.95	1.50	.93
R^2	.33	.29	.38	.35
...versus elevation-based valleyness v_e				
Coefficient	2.33	3.23	2.34	3.23
Intercept	1.23	.56	1.21	.52
R^2	.37	.30	.40	.35
...versus combined valleyness v				
Coefficient	2.18	3.01	2.17	3.00
Intercept	1.35	0.72	1.34	.70
R^2	.37	.32	.41	.37

A drawback of the RMA regression method is that its regression coefficient cannot be tested for statistical significance. However, the positions of the 95% confidence intervals for the regression gradient clearly hint at the slope being significantly different from zero (cf. Vittinghoff et al. 2005: 42). Legendre and Legendre (1998: 511), however, suggest that in the case of RMA regression the confidence intervals may neither be informative and instead propose to test the correlation coefficient *R* according to McArdle (1988). In fact, all correlations between algorithmic valleyness and variables in Table 12 are significant at the 1% confidence level, irrespective of using (parametric) Pearson correlation or (non-parametric) Kendall's Tau and Spearman's Rho.

The arrows in Fig. 75 mark areas of notable outliers of the regression. Closer examination of the stimuli flagged as suspected plains in Section 6.4.4 showed that indeed many of those lie in the indicated region of the scatterplots. This will be dealt with in the next section.

Exclusion of suspected plains. As detailed in Section 6.4.4 the presence of potential plains in the stimulus images may have affected some of the results, although the analysis of the indicator variable did not yield a significant difference (p = 0.171). As a consequence the regressions were also done using only the stimuli which were regarded unaffected by this effect. Limiting the sample to only such stimuli left a dataset of 83 (instead of 100) records. 15 out of the 17 affected stimuli were to be found in the lower right quadrant of the graphs, below the regression line. Only two were above the regression line. Equally to before, reduced major axis regressions were applied on the data subset. The regressions can be seen in Fig. 76. The residuals of all regressions were found to be normally distributed using Kolmogorov-Smirnov tests.

In all depictions in Fig. 76 one can see that the clutter below the regression line at the high end of algorithmically derived valleyness has been considerably lessened in comparison to Fig. 75 or, in the case of v_{median}, almost completely removed – the most notable exception to this is denoted with an arrow in Fig. 76 (bottom-most right). This removal of scatter naturally leads to a slightly better regression fit as can be seen from Table 13, which shows the regression parameters including confidence intervals. The removing of potential plains out of the dataset has increased the regressions' gradients and improved all models' fits expressed by R or R^2.

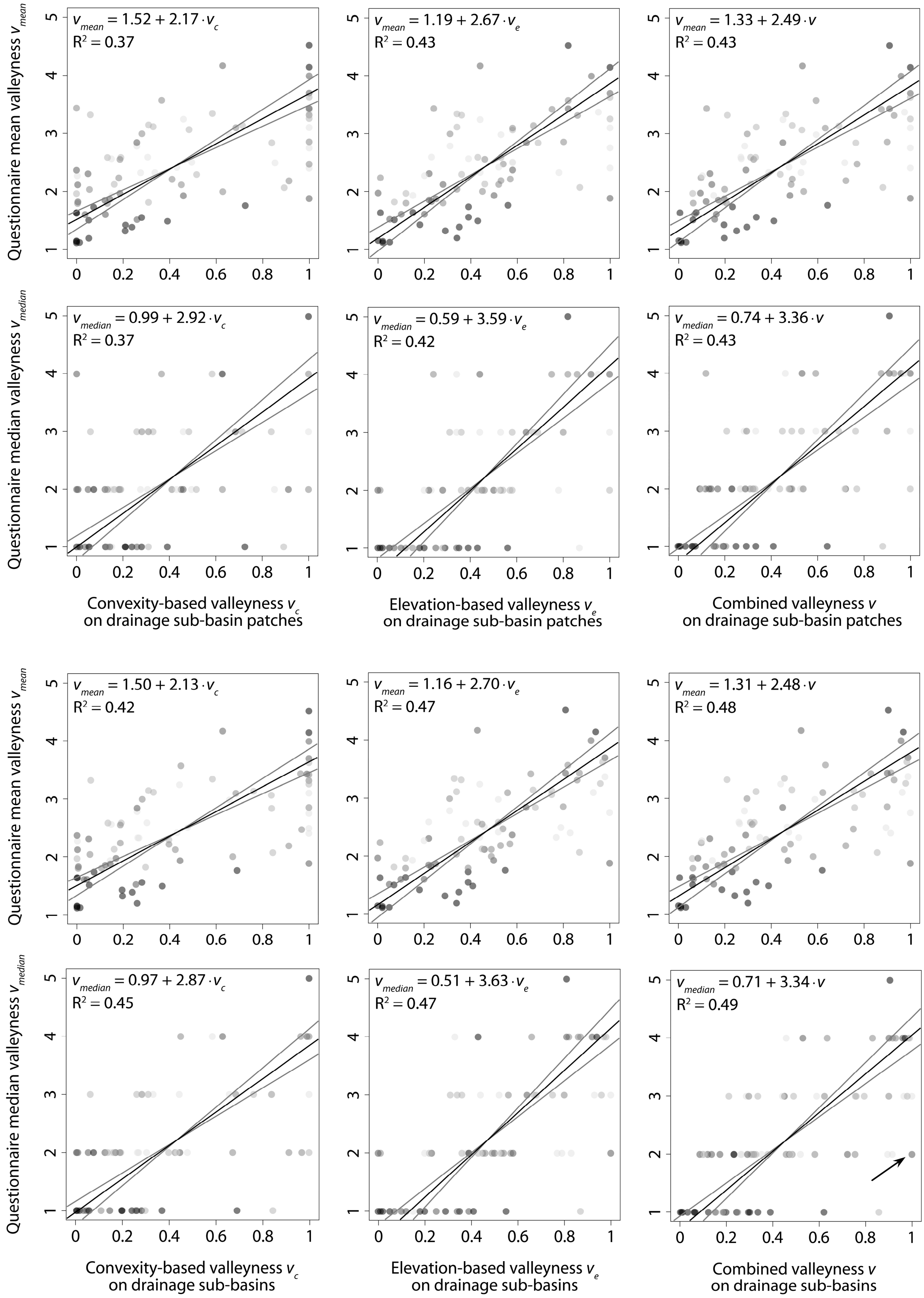


Fig. 76: RMA regressions between algorithmically derived valleyness measures - v_c, v_e and v - and v_{mean} and v_{median}, respectively, where stimuli marked as suspected plains where excluded from the regression and the display. Grey lines represent the 95% confidence intervals for the regression's gradient. The dots representing the stimuli are classified into 5 quantiles of uncertainty u and coloured accordingly; dark: low uncertainty, light: high uncertainty.

Looking at colour-coded scatterplots in the background of the regression graphs in Fig. 76 it seems that questionnaire participants were generally more certain about the judgment of stimuli on either end of the valleyness spectrum. Stimuli which posed more problems were rather located in the middle of the valleyness spectrum. This nicely advocates the concept of *core* and *fringe instances* of the category valley and of prototypicality in general, where *core instances* were estimated better (less ambiguously) and *fringe instances* less so (see Section 2.1.6). Stimuli at the lower end of valleyness, however, can be regarded even further away from the valley concept than *fringe instances*. In fact, those may be *fringe* or even *core instances* of an opposing concept.

The colour-coding of the scatterplots in Fig. 76 can also lead one to suspect that the data points which are more affected by uncertainty as operationalised in equations (23, 24), tend to be less well represented by the regression line. Thus, additionally to the standard measures of R and R^2 a weighted correlation R_w has been computed according to Bills and Li (2005: 838) and Greenacre (2007: 229) using simply inverted uncertainty as weights:

$$[0, 1] \ni w = 1 - u \tag{25}$$

During the computation of weighted correlation the software *R* adjusts the weights further to make them sum up to 1. Values of the weighted coefficient of determination R_w^2 are contained in Table 13.

As can be seen in Table 13, as a tendency with regard to all measures of determination and correlation, the drainage sub-basin based approaches perform slightly better than those based on sub-basin patches. The elevation-based valleyness approaches perform better than the convexity-based ones. This may be due to a real advantage and/or to the clearly larger footprint of the latter ones (computation of a derivative in a zonal computation rather than reliance on local elevation only). However, v which combines the convexity-based and the elevation based valleyness measures performs best of all methods – especially when computed on drainage sub-basins. Overall, the proportion of variance explained by the RMA regressions is moderate (40–50%). Regarding the weighted correlation coefficients, all pairs of variables do perform better; values of R_w^2 are consistently higher than R^2 throughout all regression combinations.

Table 13: RMA regressions of v_{mean} and v_{median} on algorithmic valleyness, where suspected plains were excluded from the analysis (CI: confidence interval). Confidence intervals are based on bootstrapping with 10000 iterations.

Regression...	based on sub-basin patches		based on sub-basins	
	v_{mean}	v_{median}	v_{mean}	v_{median}
...versus convexity-based valleyness v_c				
Coefficient	2.17	2.92	2.13	2.87
Coefficient 95% CI	[1.82, 2.58]	[2.45, 3.48]	[1.81, 2.52]	[2.44, 3.38]
Intercept	1.52	.99	1.50	.97
Intercept 95% CI	[1.34, 1.66]	[.76, 1.19]	[1.33, 1.64]	[.75, 1.16]
R (Pearson)	.61	.61	.65	.67
R^2	.37	.37	.42	.45
R_w^2	.42	.42	.48	.50
...versus elevation-based valleyness v_e				
Coefficient	2.67	3.59	2.70	3.63
Coefficient 95% CI	[2.26, 3.15]	[3.04, 4.25]	[2.30, 3.17]	[3.09, 4.27]
Intercept	1.19	.59	1.16	.51
Intercept 95% CI	[.97, 1.38]	[.26, .81]	[.94, 1.35]	[.22, .77]
R (Pearson)	.66	.65	.68	.68
R^2	.43	.42	.47	.47
R_w^2	.49	.47	.52	.52
...versus combined valleyness v				
Coefficient	2.49	3.36	2.48	3.34
Coefficient 95% CI	[2.11, 2.94]	[2.84, 3.97]	[2.12, 2.91]	[2.85, 3.90]
Intercept	1.33	.74	1.31	.71
Intercept 95% CI	[1.13, 1.50]	[.47, .97]	[1.11, 1.47]	[.46, .93]
R (Pearson)	.66	.65	.69	.70
R^2	.43	.43	.48	.49
R_w^2	.49	.48	.54	.55

Analysis of outliers. Fig. 77 shows regression between v_{median}, v_{mean} and v for drainage sub-basins. The thicker lines are offset from the regression line. All data points falling outside this margin of tolerance are indicated by their ID. The respective stimuli are depicted in Figs. 78 and 79 according to their position relative to the regression line in Fig. 77. Figs. 78 and 79 show under every picture the stimulus ID along with some statistics and a map of valleyness with the photographer's location marked by a dot in the centre (note that the azimuths of the photographs are not known, unfortunately). Subsequently, the aforementioned ID is referred to in the text in square brackets "[ ]".

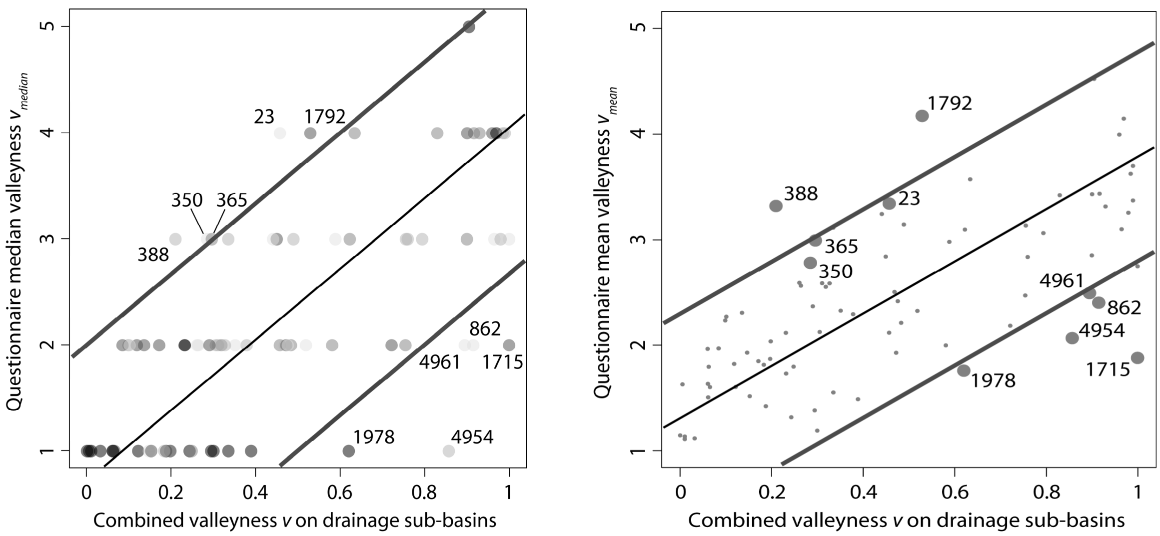
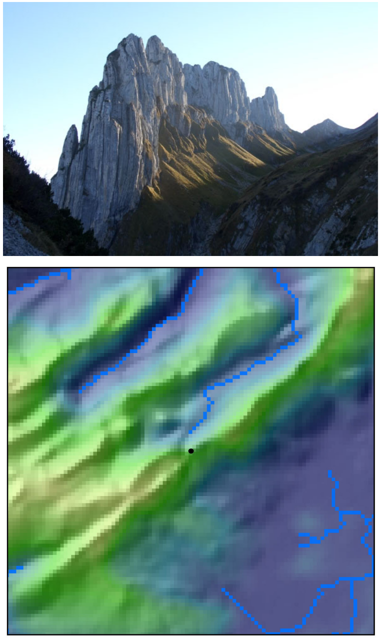


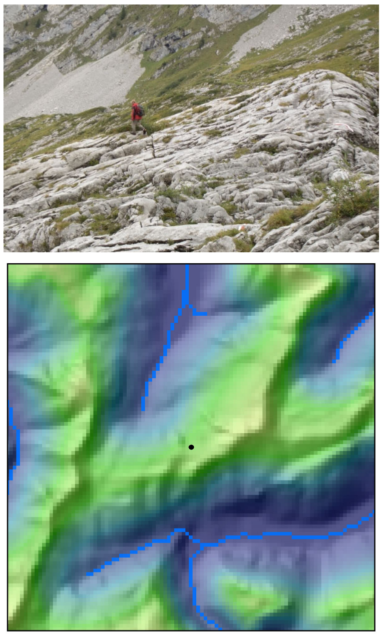
Fig. 77: Outliers with respect to the regression of v_{median} and combined valleyness v on drainage sub-basins (left); the same stimuli images highlighted in the regression of v_{median} and v on drainage sub-basins (right).

[350, 365, 862, 1715, 4954, 4961] in Figs. 78 and 79 share the circumstance that their perspective is constrained. Judging valleyness from these pictures is hard. [350, 862, 4954, 4961] do have high uncertainty values up to 0.90. Of the other stimuli [23] has a high, [388] a medium uncertainty.

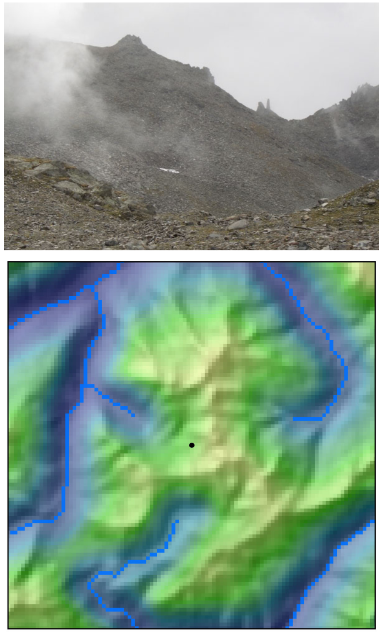
[350, 365] give especially few clues to valleyness other than material which may indicate that the location is at a higher altitude. [862] could be seen from a valley floor or from a neighbouring ridge or mountain. [4961, 4954] are very similar in that they both show a relatively steep view into a valley. [4961] shows the valley floor, [4954] breaks of slope in the opposing valley side. Interestingly, [4961] received higher valleyness estimates than [4954] although they could be shot from the same location and, looking at the maps, in fact were taken from locations similar in nature. However, both pictures give no clue as to what the situation may look like behind/above the observer. [1715] finally has clear indications that it was taken at high altitudes, however, the local surface form is not easily intelligible; the perspective is too narrow. [23] is rather special; maybe some participants judged the image contents rather than the position, since, while the location of the observer is not easy to assess, there is a conspicuous topographic depression in the centre of the stimulus image. [1978] shows a ridge separating two topographic depressions. However, the ridge the observer is standing on is also considerably lower than the topographic eminence on the left and, most probably also, on the right.



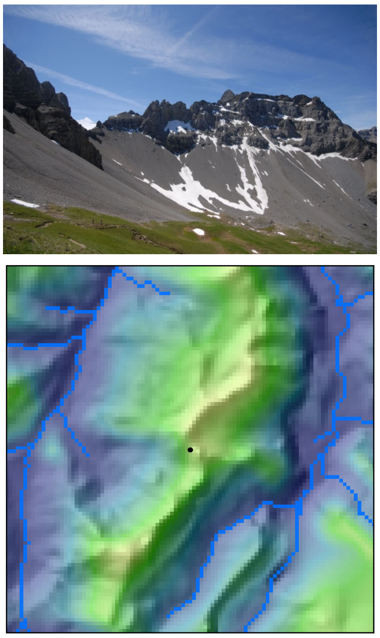
23
v_{median}: 4; v_{mean}: 3.34
v_{std}: 1.24; rV_{99}: 7.8%; u: 0.66
patch v: 0.46; basin v: 0. 46



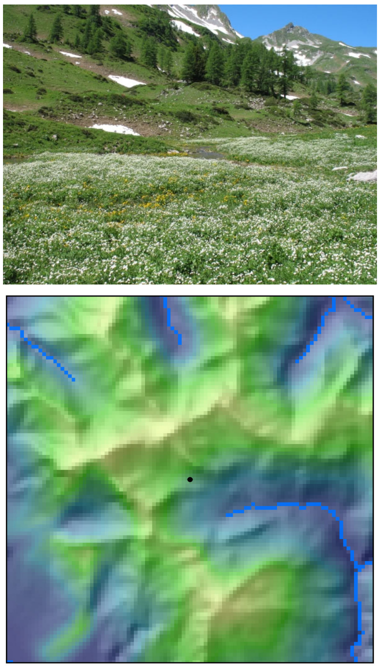
350
v_{median}: 3; v_{mean}: 2.78
v_{std}: 1.18; rV_{99}: 11.2%; u: 0.75
patch v: 0.28; basin v: 0.28



365
v_{median}: 3; v_{mean}: 2.99
v_{std}: 1.25; rV_{99}: 2.4%; u: 0.47
patch v: 0.30; basin v: 0.30

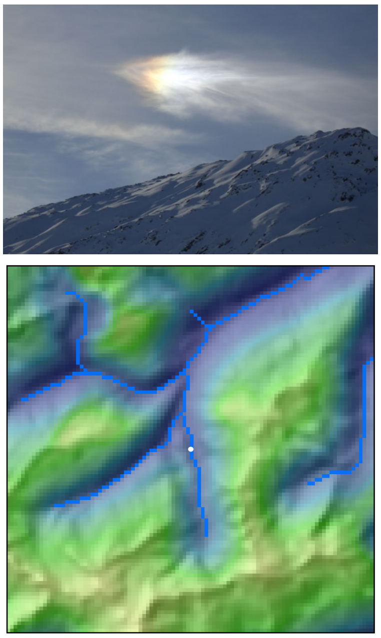


388
v_{median}: 3; v_{mean}: 3.32
v_{std}: 1.29; rV_{99}: 3.7%; u: 0.55
patch v: 0.21; basin v: 0.21



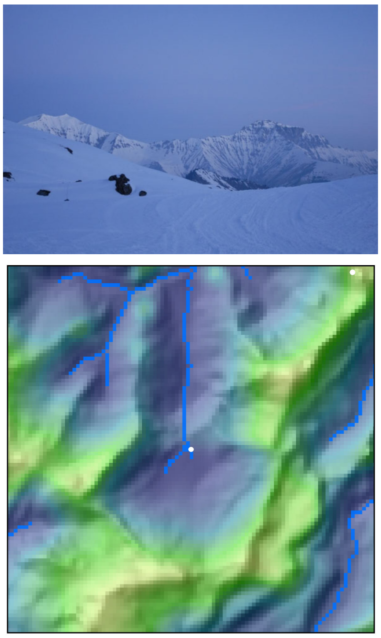
1792
v_{median}: 4; v_{mean}: 4.17
v_{std}: 0.96; rV_{99}: 2.3%; u: 0.29
patch v: 0.53; basin v: 0.53

Fig. 78: Stimulus images associated with the outliers above the regression line in Fig. 77.
Maps of smoothed v are at scale 1:200,000, i.e. one side measures 10 kilometres.
The colour scheme for v is the same is in Fig. 69, streams are highlighted in blue.



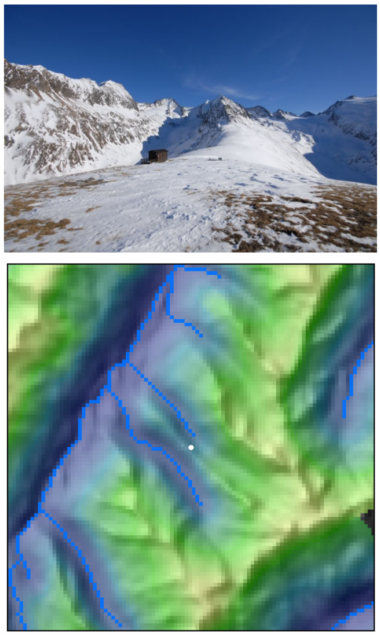
862

v_{median}: 2; v_{mean}: 2.40
v_{std}: 1.13; rV_{99}: 10.6%; u: 0.70
patch v: 1.00; basin v: 0.92



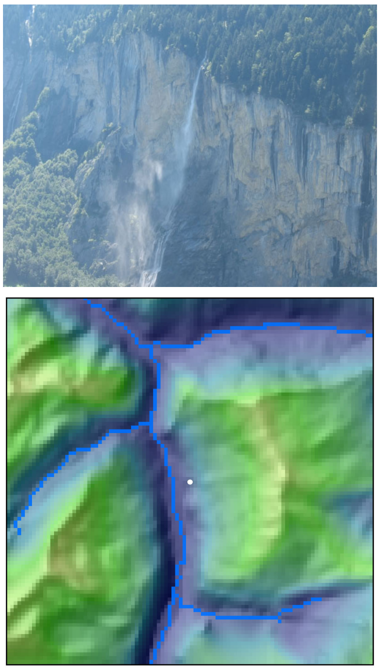
1715

v_{median}: 2; v_{mean}: 1.88
v_{std}: 0.94; rV_{99}: 5.0%; u: 0.38
patch v: 1.00; basin v: 1.00



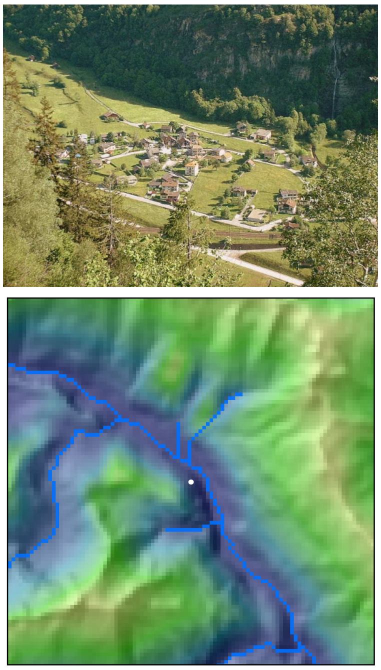
1978

v_{median}: 1; v_{mean}: 1.76
v_{std}: 1.00; rV_{99}: 0.9%; u: 0.27
patch v: 0.64; basin v: 0.62



4954

v_{median}: 1; v_{mean}: 2.07;
v_{std}: 1.33; rV_{99}: 5.9%; u: 0.65
patch v: 0.88; basin v: 0.86



4961

v_{median}: 2; v_{mean}: 2.49
v_{std}: 1.58; rV_{99}: 2.6%; u: 0.68
patch v: 0.72; basin v: 0.90

Fig. 79: Stimulus images associated with the outliers below the regression line in Fig. 77.
Maps of smoothed v are at scale 1:200,000, i.e. one side measures 10 kilometres.
The colour scheme for v is the same is in Fig. 69, streams are highlighted in blue.

Looking at Fig. 77 one can see that in terms of v_{mean} many stimuli are less clearly or not at all anymore outliers (e.g. [23, 350, 365]); the algorithmic valleyness of some of the others shall be briefly discussed here.

[388] is located in a first order drainage basin near the drainage dividing ridge. v_c is with 0.06 already very low, because the distance bins also encompasses part of the drainage divide; v_e is 0.36, since [388] is already very high in the drainage basin. While the image [388] can be imagined to be taken from a valley, most participants would probably deem the location less valley like from the map.

[1792] is located on a mid-slope position with regard to the stream. v_c is still high (0.63) and would correlate better with the estimates, but v_e is with 0.43 already considerably lower. Considering the similarities between [388] and [1792], maybe participants judged [1792] more valley-like because of the relatively abundant vegetation and the flat foreground.

[862] is an interesting case where too little information led questionnaire participants astray. Looking at the map it becomes clear that the image was indeed taken from within a valley. The photographer's location is exactly on a thalweg/stream cell. Consequently, the questionnaire answers also exhibited a rather large uncertainty with this stimulus.

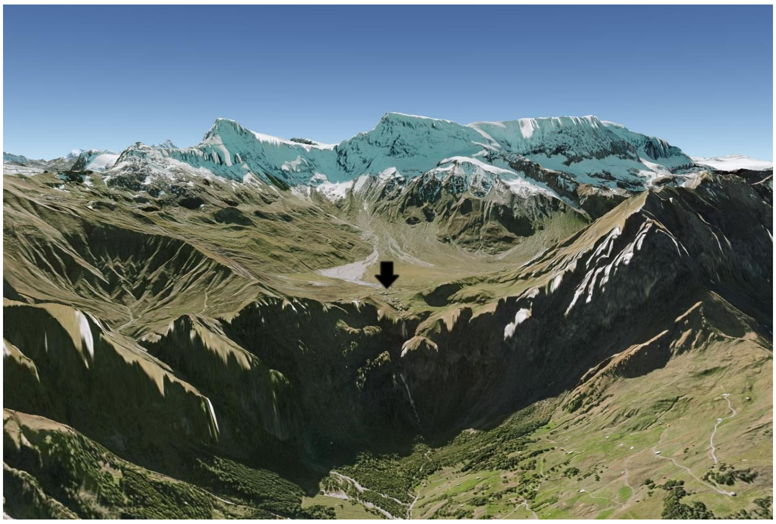


Fig. 80: View onto the photographer's location for stimulus [1715].

[1715] is another interesting stimulus. Its location was judged quite not valley-like, maybe owing to the indication of high altitude and inability to really see into a valley. Fig. 80 depicts the photographer's location viewed frontally on the Engstligenalp above Adelboden as taken from Google Earth (2009). Its German-speaking Wikipedia (Wikipedia DE 2009) entry characterises Engstligenalp both as a plateau and as valley floor. The photographer's location is part of a headwater catchment of a very short stream (see map in Fig. 79). Had that stream not been initiated, the location would have been joined to the downstream drainage sub-basin and definitely v_e, maybe also v_c would have attained markedly lower values primarily because of the large vertical step immediately downstream. However, that is not to say, that the present algorithmic assessment of [1715] is off; rather it is a very difficult case.

Comparing the maps in Fig. 79, [4954] and [4961] are characterised very similarly by the algorithm, since they have similar locations. Both are close to the thalweg but considerably above it (208 and 344 metres, respectively). [4954] obtains a high v_c value since it is located in Lauterbrunnental, a *U-in-U* valley (i.e. there is considerable convexity still above [4954]), the same applies to v_e. [4961] on the other hand is under stronger influence of the opposite valley side which extends farther and higher and this raises the probability of [4961] to obtain a high valleyness value. Computed on drainage sub-basin patches rather than drainage sub-basins v for [4961] would be a 0.72, i.e. somewhat lower. Summarising, probably both stimuli's assessment by the questionnaire participants suffered to some degree from lack of information.

Deeper investigations of individual stimuli and their associated questionnaire results are given in Appendix F. There the stimuli with the highest and lowest valleyness, with the highest and lowest spread of valleyness and with the highest and lowest amount of uncertainty involved in the estimation are presented. Those considerations give a deeper insight into some of the potential processes involved with judging the valleyness of a location based on a single image.

6.4.6 Uncertainty in the estimation process as a function of valleyness

Having investigated both the absolute distributions of valleyness estimates and their relation to algorithmic valleyness computations, it may be insightful to look closer at the explicit (i.e. indicated) and implicit uncertainty involved in the questionnaire participants' judgements. Partly, this brief analysis was inspired by an e-mail from a questionnaire participant listed in Appendix G (e-mail 4).

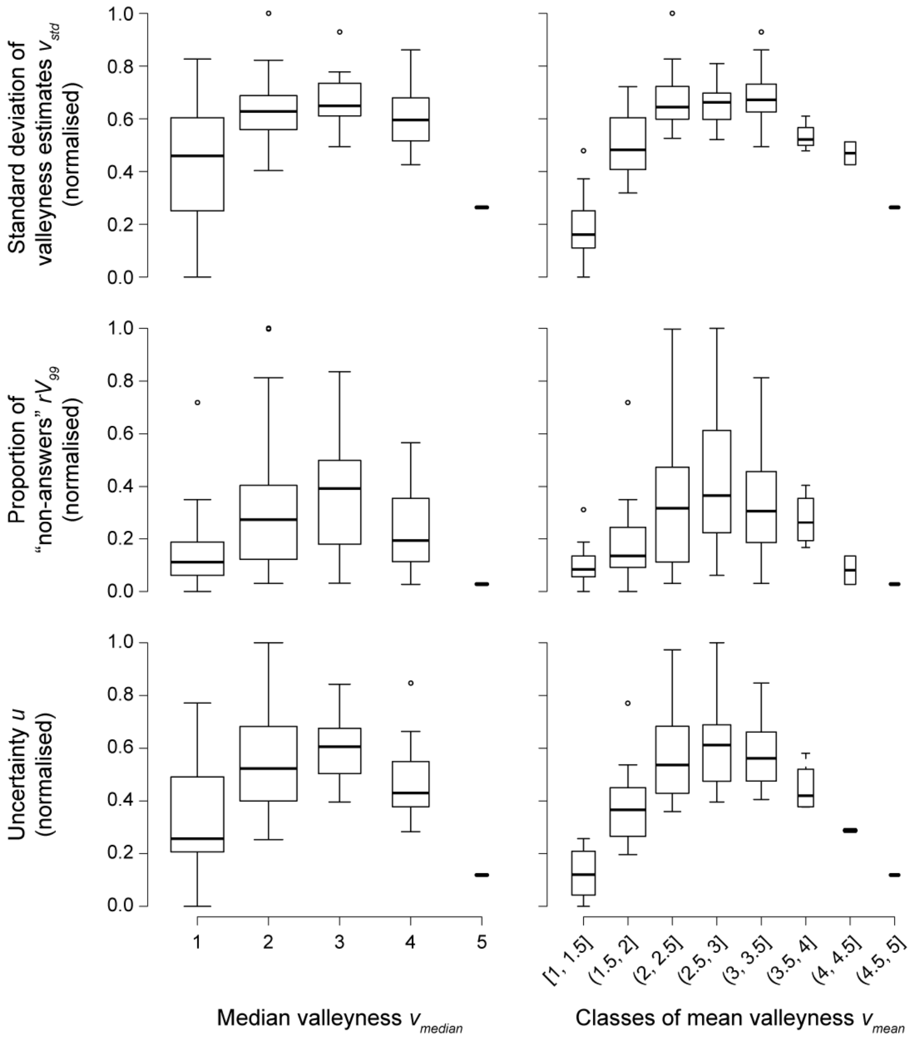


Fig. 81: Boxplots of normalised uncertainty-related statistics of valleyness estimates grouped according to v_{median} and v_{mean}.

Fig. 81 shows boxplots of two statistical measures (standard deviation of valleyness estimates v_{std} and the proportion of "non-answers" rV_{99} (equation 22 in Section 6.4.5)) which are deemed linked to uncertainty and which are contained in the uncertainty measure u (equation 24 in Section 6.4.5). The boxplots are grouped on the x-axis according to v_{median} and v_{mean} and their widths are scaled according to the number of observations they represent. The plots reveal that v_{std} is higher for low (< 3) than for high valleyness (> 3). For v_{median} of 1 v_{std} shows considerable variation. This variation is much lessened when boxplots are drawn with respect to classes of v_{mean}, because there only the most extremely un-valley-like features reside in the lowest class. So, regarding these situations there is not so much ambiguity in participants' responses. The situation is similar for rV_{99}; also there – as a tendency – lower valleyness estimates seem to be associated with higher uncertainty, this time expressed by the participant indicating not being able to provide an answer to the questionnaire item at hand.

Besides the characteristics of the boxplots near the lower and upper hand of the valleyness spectrum one should also look at the ‘curve’ described by the central tendency indicated by the boxplots. This curve always resembles an inverted U. This is not surprising for v_{std}, where it is almost a necessity, since v_{std} of an item and its central tendency are interlinked. When the valleyness estimate is near the centre, there is more potential for variation of the individual answers around this central value than there would be if the central value were near one of the ends of the valleyness range. However, the inverted U shape also holds true for rV_{99}. Being in fact missing values, these – other than v_{std} – are not interrelated to the central tendency of valleyness estimates. Still, they indeed indicate (and thus reinforce the previous observation) that uncertainty is high near the middle of the valleyness spectrum. The twist to this is, however, that all curves ‘lean’ towards the left, i.e. are right-skewed or positively skewed.

Thus, summarising, we can observe that the uncertainty involved in the valleyness estimation process seems to be higher for scenes which are eventually judged un-valley-like than for scenes which are judged valley-like. However, the ambiguity regarding extremely un-valley-like features is usually not big. Upon closer examination, this seems to be supported both by the boxplots in Fig. 81 as well as by the more in-depth discussion of stimuli in Appendix F.

6.5 Conclusions

This section has presented a possible approach to integrating semantic knowledge into a characterisation algorithm for valley side slopes. Further, grounded on the discussion of the characteristics of the landform at hand (valleys) this algorithm was combined with the algorithm presented in the first two case studies to yield a measure which was termed valleyness. More precisely, a set of valley side characterisation algorithms in conjunction with the valley floor delineation resulted in a set of valleyness measures – convexity-based, elevation-based and combined valleyness.

These semantically constructed, objectively computed, DEM-based valleyness measures were compared to assessments of photographs given by some 800 participants in a human subject experiment. While some tendencies of differences between members of different expertise groups were present, these differences did not prove themselves statistically significant and all questionnaire answers could be integrated for the comparison with the algorithmic results.

The comparison of the questionnaire results with the valleyness measures gave a mixed result. Clearly, the participants' answers correlate with the algorithms' results and the correlations are statistically significant. However, the proportion of variance explained even with the best fitting approach considering opposing valley sides together and computing combined valleyness remains 49% (55% if data points are weighted according to uncertainty). This result of course leaves room for improvement.

The presented experiment is to our knowledge the first of its kind. We strongly encourage that similar, potentially improved, experiments are carried out with other methods of land surface form characterisation, also for different landforms such as topographic eminences. While such evaluation of objective algorithms against subjective human assessment can demand a considerable effort, it can provide valuable insight into the perception and conceptualisation of land surface form by humans and about the capability of objective algorithms to mimic these. However, equally importantly, the experiment conducted also exhibited some drawbacks which shall be highlighted here.

Several factors probably influenced and biased the participants' judgement of valleyness. Depending upon the position of the horizon, the vertical and the relative horizontal viewing direction of a stimulus the judgement of participants differed statistically significantly. However, as has been noted, all these variables to some degree sensibly vary along with the position of an observer in a valley and are thus also linked to the valleyness of the observer's location. Conversely, the presence of sky, snow and rock in stimulus images did in this study not change participants' judgement. However, this effect was not assessed in an isolated manner. To properly assess it, one would need to present participants with different versions of the *same* stimuli which differ only by the presence or absence of one such feature. Another hint that the results of this analysis need to be considered cautiously is also that the presence of potential plains in the stimuli was considered to be a *not* statistically significant influence – however, with a low *p*-value. When subsequently the stimuli with potential plains where excluded from the regression, the model fits improved markedly, however. Hence, it is assumed that the content of an image may influence participants in various dimensions apart from shape. In this study these effects could not be completely excluded.

Also, we suggest thinking about whether a similar future study should employ some kind of panoramic images in order to better enable participants immersion into the landscape.

With the present stimuli in some situations participants had to use clues from the images to have a (hopefully informed) guess as to what may lie outside the view, for instance, behind the photographer. Appendix F contains a more detailed discussion of groups of individual stimuli, which were judged similarly by questionnaire participants, and provides further insights into what participants might have based their judgement of valleyness on and also how participants may have been biased in some instances.

Along with a suggestion by David Mark (oral communication, 3 September 2009) it is thus proposed that further studies first conduct pre-tests on a set of stimulus images thereby first confirming what exactly participants see in the stimuli (e.g. do they see a valley?). This could also be done in a qualitative fashion. Alternatively, as briefly sketched out above, the presented shape could be kept static and other factors such as viewing direction and materials could be varied to further elucidate factors apart from shape which may influence judgements of landforms.

Result-wise, while the algorithms' results seem mostly sensible, the quantitative evaluation highlighted room for improvement. How much this is owed to shortcomings of the algorithms and how much to shortcomings of the method of validation (e.g. static images versus more immersive techniques such as panoramic images) has to be left open. Certainly, the valleyness algorithms are able to capture a substantial proportion of the essence of the landform *valley*.

"He sat in the coach with cold resignation as they drove out of the valley toward the west. He cared little where they were taking him; on the several occasions where the coach was put at risk by the bad road, he remained seated quite calmly; nothing mattered to him at all. In this condition he traversed the mountains. Towards evening they reached the valley of the Rhine. Little by little they left the mountains behind, now rising in the red glow of dusk like a wave of dark blue crystal and on whose warm crest the red rays of evening played; above the plain at the foot of the mountains lay a shimmering bluish web. Night was falling as they approached Strasbourg; a high full moon, all the distant objects dark, only the nearby mountain forming a sharp line, the earth like a golden goblet over whose rim the golden ripples of the moon foamed. Lenz stared out quietly, no misgivings, no stress, just a dull anxiety building up inside him the more the objects disappeared into the dark. They had to stop over for the night, he made several more attempts on his life but was too closely watched. The following morning he entered Strasbourg under dreary rainy skies. He seemed quite rational, conversed with people; he acted like everybody else, but a terrible emptiness lay within him, he felt no more anxiety, no desire; he saw his existence as a necessary burden. –
And so he lived on."

from *Lenz* by Georg Büchner

7 Reflections and outlook

This chapter firstly revisits the research questions from Section 2.5 and summarises briefly the respective research which was carried out. Secondly, the contributions this thesis made to the body of research of geomorphology, geomorphometry and geographic information science are listed and detailed. Subsequently, insights which were gained and observations which were made during the process of researching for this thesis will be shared, before, lastly, a threefold outlook will investigate potentially emerging research strands and trends and will suggest some leads to follow up on.

7.1 Revisiting the research questions

In Section 2.4 we identified two main research gaps in the ontology of landforms and the characterisation of landforms from DEMs. Regarding the first the thesis set out to elucidate the ontology (in the computer science sense) of landforms. This resulted in the reasoning in Chapter 3 and in a tentative taxonomy of landforms. In this process we, naturally, also considered some issues around landforms which belong to the philosophical meaning of the term ontology. Regarding the second research gap we confined ourselves to *valley* landforms. In Chapters 4 to 6 three case studies were carried out, each of which aimed at a slightly different research focus. In the first case study we devised and evaluated an algorithm for the delineation of valley floors. In the second case study we used the results of the first one to undertake a geomorphological study of sediment storage in the European Alps. In the third case study, the valley floor delineation algorithm was complemented with different approaches for valley side slope characterisation and the new measure of valleyness was subsequently evaluated in a human subject experiment. In the remainder of this section we will revisit the research questions we have formulated in Section 2.5 and briefly detail how this research has addressed those research questions.

RQ1 What landforms are often referred to in reference works and standards?

RQ2 How are these landforms defined? How are different landforms related to each other? Can a taxonomy of landforms be developed?

In response to these questions we investigated the landform-related contents of six standardisation works (WordNet, SDTS, DIGEST, Ordnance Survey Hydrology Ontology, Alexandria Feature Type Thesaurus and the Geography profile of the Suggested Upper Merged Ontology). In many areas they were complemented by additional geomorphologic literature and reference works as well as the Oxford English Dictionary which provided a more folkloristic approach. Together, we deemed these sources representative of what many people in diverse fields consider important instances of the class of landforms. Only in few instances the semantic depth of the standards was drastically extended by additional literature, namely for dunes, moraines and karst features.

In Section 3.4 we thoroughly discussed the characteristics (definitions, relations) of landform categories and eventually came up with a reconciled tentative landform taxonomy (Fig. 29), a summary of shape characteristics (Figs. 30 and 31) and process realms (Fig. 32; all in Section 3.4).

RQ3 How can a landform be formalised to be treatable within a GIS?

RQ4 Can landform concepts be exploited for practical use in, for example, a characterisation algorithm?

Section 3.4 bundled information regarding possible formalisations of landforms; for example, shape, dimensions, context, material, process realm were specified if known from the literature.

Regarding RQ4, more specifically, Chapters 4 to 6 then investigated valleys and related landforms in more detail. In Chapter 4 we re-considered definitions for valleys and valley floors. The descriptions of these concepts helped in formalising valley floors dependent upon context (close spatial association with thalweg) and shape (relatively planar and relatively flat). We then implemented the operationalised formalisation in a region growing algorithm which, we hypothesised, was able to delineate valley floors from DEMs. In

Chapter 6 the valley floor delineation algorithm was complemented by three different approaches to characterising valley side slopes. Again, starting from a discussion of the concept, potential hints for formalisation were identified (convexity and relative elevation). In compliance with observations and considerations regarding the definition of the category of valleys, approaches based on these formalisations could only be sensibly implemented fuzzily. The results of both strands of algorithms (valley floor delineation and valley side slope characterisation) were then amalgamated into a single terrain parameter which we termed "valleyness".

RQ5 Can the characterisation algorithm successfully extract the landform in question from a DEM?

Apart from qualitative visual examination, several other approaches at validating of the "success" or testing the plausibility of the developed algorithms were undertaken.

For the valley floor delineation we compared to folk notions of a specific prealpine valley in Switzerland (Gürbe valley) and its neighbour (Aare valley). Comparisons for this excerpt of the complete result were convincing insofar as no conflicting evidence regarding the extent of the valley (mostly, the valley not the valley floor could be analysed) was found. Additionally, the valley floor delineation was compared to the six-fold morphometric feature classification both in the Gürbe and Aare valley as well as over the whole study area (Switzerland). These analyses showed – mostly through cross-tabulation statistics – that the two characterisations mostly supported each other but that the method's results cannot be easily replicated by a morphometric feature classification.

For the valleyness measures the chosen method was more complex. Through a human subject experiment involving the assessment of photographs we were able to gather data which could be regarded as "ground truth" (though not free of bias). The comparisons of our computations with the human judgment showed an alignment of our valleyness measure with the tendencies of the experiment participants. Correlation analysis found statistically significant relations.

RQ6 In turn, to what use can an extracted landform be put, in, for example, geomorphology and in the description of landscape?

Chapter 5 applied the valley floor delineation developed and tested in Chapter 4 onto a geomorphological problem context. The results of our algorithm were very favourably compared in thirteen drainage basins to results obtained by Hinderer (2001) through time-consuming manual mapping. Making use of a relation in Hinderer (2001) we were not only able to characterise sediment distribution in the European Alps by means of the areal extent but also the occupied volume. The analyses showed several interesting results like, for instance, that large valleys hold a disproportionately large share of all sediments. The derived data can be used within geomorphology, for example, as input to landscape evolution models and it allows estimations of process rates since the last glacial maximum.

The fuzzy valleyness developed and tested in Chapter 6 may be of less immediate interest in geomorphology than the valley floor delineation. Still we are confident that the valleyness measure may be used as a terrain parameter there as well as within qualitative environments dealing with human concepts. Although it was not within the scope of this thesis, in Chapter 6 we tried to make a point that the valleyness measure is indeed informative and may be of great use, for example, in landscape form descriptions or – more specifically to the human subject experiment carried out – in the annotation of georeferenced documents.

7.2 Contributions

This thesis provided the following main contributions.

Listing and discussion of landforms. We compiled a listing of landform-related categories out of six reference works, complete with thesauric or categorical relations. Overall, the listing contains 185 landform-related categories (63 for topographic eminences, 56 for topographic depressions, 18 for topographic plains, 31 for landform elements and 17 remaining; not accounting for the landform-related terms we excluded early in the process for several reasons (see Section 3.2.8). These were grouped and thoroughly discussed regarding their shape, dimensions, material and coming into existence. This approach was supported by inclusion of geomorphologic and geologic dictionaries and textbooks.

Taxonomy of landforms. Besides the insights mentioned above investigation of the realm of landforms resulted in a taxonomy of landforms as a tangible result. Also, we graphically summarised shape characteristics (Figs. 30 and 31) and process realms (Fig. 32; all in Section 3.4) of the landform categories in our taxonomy. For ordering purposes we proposed the three-fold super-categorisation into topographic eminences, depressions and plains.

Implementation of an algorithm to delineate valley floors. We developed a top-down (i.e. semantically informed) delineation algorithm for valley floors from a coarse DEM (100 metres resolution). In this, we adopted an approach which could be likened to the semantic import model in classification; however, our method went further than that. The semantics were not analysed to merely yield classification thresholds but also to develop other aspects of the algorithm: for example, the kind of the algorithm (region growing) and certain spatial considerations (drainage sub-basin constraining, spatial association of valley floor with thalwegs).

Adaptation of valley floor delineation algorithm to geomorphologic research context. Subsequently we adopted the valley floor delineation algorithm to be used within a geomorphologic research context. This encompassed the introduction of a filtering procedure to convert the "network of pearl necklaces" (network of numerous thalwegs with sediment storage areas as beads) into about 18,000 distinct sediment storage areas through operations from mathematical morphology. Subsequently, sediment storage areas were transformed into sediment storage volumes.

Geomorphological study of sediment storage. With our algorithm for the first time a large-scale automatic delineation of sediment storage areas in a mountain-belt was carried out. The delineation of sediment storage areas matched an earlier, manually derived dataset very well and proved valuable in conducting additional geomorphological analyses such as the investigation of size-frequency relationships of both areas and volumes and the hypsometric distribution of sediments.

Implementation of algorithms to compute valleyness. Again starting from definitions for valleys and from folk notions of the category we hypothesised that a fuzzy measure of valleyness could be computed using convexity and relative relief within drainage sub-basins in conjunction with the crisp valley floor delineation. We implemented three variants of valleyness algorithms.

Validation of valleyness measure. The results of the valleyness algorithms were subjected to comparisons to data we gained in a human subject experiment involving images as stimuli. While the experimental procedure was not completely free of bias, the comparisons to our valleyness measures gave promising results. A substantial and statistically significant amount of the variation in the human judgement of valleyness could be explained by all of our valleyness measures.

7.3 Insights

Through the occupation with many intricacies in the field of landform (element) studies several insights were gained, some of which shall be mentioned here.

Scope of existing landform analysis literature. We were surprised to discover during the literature analysis that not many approaches exist to analysing what we deem landforms (rather than landform elements). Also from the relatively few approaches dealing with landforms, practically all seemed to focus on some kind of topographic eminence whereas we could find almost nothing about topographic depressions. This revelation then also directed our research focus in the later phases where we concentrated on a small excerpt of our taxonomy.

Similarly we found that many approaches aim at deriving generically defined features (often landform elements) and that relatively few authors actually had made the extra step of pondering ontological questions and about the landform categories they were after. This circumstance motivated us to try and 'nudge' the 'two worlds' (of ontological research and applied research of extraction algorithms) somewhat closer together.

Scale dependence. In our review of the literature as well as in Straumann and Purves (2007) we occupied ourselves with the scale dependence of both terrain parameters and landform (element) classifications. This issue has been addressed to some degree with the advent of algorithms working at multiple scales such as those by Wood (1996). However, one still has to choose *a set* of scales of analysis. In our approaches to landform delineation and characterisation we thus tried to avoid this problem by choosing drainage sub-basins as a region of analysis rather than a predefined quadratic moving window. We thought and think that this approach could be valuable, since it (apart from the definition of a stream initiation threshold) is based mostly on an inherent scale of the topography which is defined by the occurrence of thalwegs, drainage divides and interfluves.

Parameter tuning. Reviewing the existing literature we also gained the impression that many methods heavily rely on sometimes large parameter sets which can be fine-tuned and which can depend on various levels of human input. This formed another motivation in our own research, namely to diminish the parameter dependence. This was to some degree facilitated by what we already presented as an advantage in the above paragraph, namely the usage of drainage sub-basins as analysis neighbourhoods.

While the valley floor delineation algorithm relied (strictly) on two parameters, namely the stream initiation threshold and the gradient criterion for region growing, the subsequent valleyness algorithms did not rely on a single parameter. All measures were computed in relation to the overall characteristics of the respective drainage sub-basin (e.g. total weighted convexity and minimum and maximum elevation). This effectively means, that the valley floor delineation only involved two parameters and that, subsequently, the valleyness measures do come at no parametric costs at all.

As a side note, the valleyness computations have the advantage that they would easily work if one switched to another method for the valley floor delineation. The latter only sets the boundary conditions for the former; and can be unplugged and switched for another algorithm easily.

Ontology of landforms. The ontology of landforms is a complex field of study. There remain many open questions in the philosophical part (*sensu* Guarino 1998) of it. These are slowly addressed by a research community around, for example, David Mark and Barry Smith. Many questions about how humans conceptualise landforms and landform elements are unresolved (see Section 2.1). However, with these questions open it is difficult and probably not sensible to advance further in the computer science part of ontology (*sensu* Guarino 1998). A thorough ontological investigation would not only come up with a taxonomy of categories. Additionally it needs a mereology and a qualitative topology, but also means to represent fields besides objects (e.g. Mark et al. 1999). The goal would be to formally implement these and to connect the geographic domain ontology to the very basic categories in one of the foundational ontologies. However, until the open questions are solved, it is doubtful (and in our opinion not sensible) that anybody tries to tackle the issues with rigorous formality.

The landform taxonomy. Through investigating geomorphologic categories we have gained significant insights. It was interesting to see the whole of the landform taxonomy (Fig. 29 in Section 3.4) and how the complexity of the taxonomic trees rooted in the three superordinate categories of eminences, depressions and plains differed. The taxonomy can provide a working basis for, for example, further investigations at a finer granularity, explicit linkage of the found landforms with landform elements or ontological studies of the individual landforms investigating (similar to Derungs and Purves 2007) what constitutes and what affects people's perception of said landforms. Importantly, we also think the landform taxonomy is detailed enough to foster research of further algorithms to characterise landforms.

Validity and extent of the taxonomy. We have briefly touched upon interpersonal and intercultural variance of landform conceptualisations (Section 2.1.7). Clearly, our tentative landform taxonomy cannot be agreed upon by everybody; still we think it can be a worthy contribution.

It was also interesting, during the building of the taxonomy, to see the seemingly uneven coverage of different parts of geomorphology. For example, karst landforms were almost completely absent from all reference works. Dunes and moraines, despite featuring a big breadth of forms, were often only contained under their summarising category and were seldom further refined to dune and moraine landforms which could be distinguished by their *shapes* rather than by their *material* and *process properties*.

Although we deemed our set of reference works to be quite general there is the inherent danger that some landforms may not be featured at all or may be badly portrayed, for example, because the respective reference was produced in a country where said landform is not, or is only seldom, found.

Conducting a geomorphological case study. The valley floor delineation algorithm was put to use within a geomorphological research context. Geomorphology lacks large-scale data regarding sediment distribution. Combining our valley floor delineation with a filter step enabled us to quantify the sediment distribution over the European Alps in a spatially explicit manner. By combining this data in turn with an earlier study by Hinderer (2001) we could provide geomorphology with new and interesting insights.

Validation of landform analyses. Through the first and the third of our case studies we gained experience in validating (or testing the plausibility of) results of landform characterisations. We did this partly through Naïve Geography knowledge (also employing the established comparison of landform extents and toponym locations) but also through a human subject experiment. Especially the latter is in our perception unique in the literature but gave us many interesting (sometimes qualitative) insights. We think that similar experiments (taking into account the weaknesses pointed out in Section 6.5) could be of considerable benefit to the study of landforms and the conceptualisation of them in humans.

7.4 Outlook

Ontology studies. We hope our taxonomy can provide a framework for future approaches to terrain characterisation from DEMs aiming for semantically rich landform objects rather than generic landform element classifications or characterisation of DEMs by derivation of simple field-like terrain parameters.

Of course, our landform taxonomy is tentative; clearly, it cannot claim to provide the ultimate solution to the incredible medley of landform-related terms which is owed to the descriptive history of geomorphology – but at least it can serve as a base for discussion. Strictly and scientifically, only researchers and practitioners in geomorphology can work towards clarification of their terminology. From a more folk-discipline viewpoint, human subject testing should reveal more and more clearly, which landform terms laypersons use commonly, which they consider to represent basic level concepts and how they are perceived and conceptualised (possibly differently in different cultures). Both these endeavours, however, cannot be achieved within the scope of a single thesis. While we do think that semantically richer approaches in landform studies could benefit from the taxonomy laid out in this thesis, much remains to be done regarding ontological studies about landforms. Presently, some of the research interest seems to be shifting away from the existing research strand to the new field of ethnophysiography, however. While the latter approach is certainly interesting, we think the more general study of landform ontology remains rewarding and important.

We are not very optimistic regarding *formal* ontologies in the realm of geomorphology, however. We advocate that the basic studies of landform concepts and conceptualisation need to be much intensified, before the community should think about building a *formal* ontology. Still, any approach towards formalisation of geomorphologic and geographic language should be welcomed, since it helps in tackling geographic subjects within geographic information science and systems. Potentially, psychology and linguistics are interesting fields to team up with in this respect.

Landform characterisation. In the field of landform characterisation we see different directions of development.

Very generally, we think it would be worthwhile to develop more characterisation algorithms dealing with landforms. This kind of algorithm lags behind algorithms for landform *element* delineation, although they are of more relevance for laypeople who probably have a better vocabulary about large-scale forms. Similarly, we think it is indispensable that geomorphologists, geomorphometrists and geographical information scientists work together towards more semantically inspired and grounded characterisations of both landforms and landform elements. Such methods would offer significantly higher information content than the ordinary generic and purely shape-based classifications.

Scale and parameter problems will remain relevant in landform studies. Regarding scale the last few years have seen significant advances. In this thesis we have tried to incorporate a 'natural' scale of analysis to landform characterisation using inherent features of the landscape: drainage basins. Conversely, some researchers may want to investigate methods which allow them to define a suitable analysis scale (e.g. Schmidt and Andrew 2005).

Regarding the parameters of methods the problem will remain how to choose them. Often this cannot be done objectively and informedly but involves some tuning or, bluntly: guesswork. Therefore we think the development will maybe go into two directions: firstly, there will be a strand which develops algorithms and methods to deal with choosing and adjusting parameters; secondly, we may see a strand of methods which tries to minimise the amount of human parameter input and thus tries to lessen the subjective judgement involved in landform studies. We would position this thesis in the latter strand.

Also, partly related to the question of scale, in the first case study we gained the impression that a combination of our valley floor delineation algorithm with the morphometric feature characterisation (or with any lower-level method) may be insightful. Such a combination may be advantageous mainly because of added information content. For example, Schmidt and Hewitt (2004) used a higher-level algorithm to re-allocate landform element features to different classes. We could envision methodologies were higher-level information could give taxonomic clues regarding lower-level features; for instance, a ridge within the extent of a valley floor could be marked as a candidate for either the *moraine* or the *esker* category.

Once we devise algorithms with the aim of mimicking human conceptualisation of landforms, we should think about validating our findings. So far, landform element classifications have sometimes been compared to soil maps or landform element chartings by experts; but up to now we have not seen examples of large-scale human subject testing involving laypeople to judge a landform characterisation. We posit that this latter approach would be the best way to go about validating or testing an algorithm which claims to produce results which are meaningful to humans. We also think that such experiments may help us learn a lot about human conceptualisations of landforms and maybe about ways to build algorithms which mimic these.

Summarising, we think that our approach (development of a semantics-based characterisation algorithms with subsequent evaluation against human judgement) is a valuable way of enlarging and improving our knowledge about landforms and their perception and conceptualisation in humans and that it should be further pursued.

Applications. Regarding applications we have mostly worked within geomorphology in our second case study. Clearly, landform extraction algorithms should be usable within geomorphology, the exact context being dependent on the landform extracted.

In our example a delineation algorithm which was originally designed for valley floors extraction was put to use to delineate sediment bodies in a mountain-belt. In this the distribution of sediment storage has been shown to be very much skewed in terms of both area and volume. Additionally, we suggested an approach to delineating the downstream transition between the domains of bedrock, mixed bedrock-alluvial and alluvial rivers. This method should be tested further as was also emphasised in the case study itself. Also, the findings could be further substantiated by applying our algorithm to other mountain chains.

In the third case study we developed valleyness measures. This can also be of interest to geomorphology; however, clearly, other potential fields of application come to mind. Such fields encompass, for example, geographic information retrieval which deals with vernacular regions or human computer interaction which in geographic information science presently develops towards easier-to-use systems through incorporation of Naïve Geography (and maybe one far day sees systems worthy of the label *Naïve GIS*).

However, investigating methods to exploit the valleyness measure in such contexts were not within the scope of this thesis. Nevertheless, in Chapter 6 we tried to make a point that the valleyness measure is indeed informative and may be of great use in, for example, landscape form descriptions or in the annotation of georeferenced documents. Future research could investigate how exactly measures like valleyness can be put to good use within such applications. For example, in our human subject experiment we simplisticly only looked at the valleyness of the photographer's location. However, with georeferenced images one could imagine scenarios where the image content is characterised using the photographer's location *complemented* with looking direction, focal length and a DEM in such a manner that exactly the geographic footprint of the viewed portion of the landscape could be computed. This (not necessarily contiguous) area could then be used together with a valleyness raster of that area to characterise the image content better than by the photographer's location alone.

We thus suggest that many goals remain to strive for in all areas this thesis tried to touch upon – landform ontology, landform characterisation from DEMs and applications of landform characterisations.

References

Strings of numbers, letters and other characters within square brackets [ ] are Digital Object Identifiers (DOIs). The referenced documents can be simply obtained via a browser call preceding the respective DOI with "http://dx.doi.org/".

A

Aandahl AR (1948): The characterization of slope positions and their influence on the total nitrogen content of a few virgin soils of western Iowa. *Soil Science Society of America Proceedings*, 13, 449–454. [cited in Pennock et al. 1987]

Adediran AO, Parcharidis I, Poscolieri M and 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 [10.1016/j.geomorph.2003.07.024].

ADL Project (2002a): Alexandria Digital Library (ADL) Feature Type Thesaurus, version 3. University of California, Santa Barbara. http://www.alexandria.ucsb.edu/gazetteer/FeatureTypes/ver070302.

ADL Project (2002b): Alexandria Digital Library (ADL) Feature Type Thesaurus, version 3. Hierarchical listing of preferred terms. University of California, Santa Barbara. http://www.alexandria.ucsb.edu/gazetteer/FeatureTypes/ver070302/top.htm.

Ahnert F (1998): Introduction to Geomorphology. Arnold, London, UK.

Allaby M (2006): A Dictionary of Ecology. Oxford Reference Online. Oxford University Press. http://www.oxfordreference.com/views/BOOK_SEARCH.html?book=t14.

Allaby A and Allaby M (1999): A Dictionary of Earth Sciences. Oxford Reference Online. Oxford University Press. http:// www.oxfordreference.com/views/BOOK_SEARCH.html?book=t13.

Alley RB, Strasser JC, Lawson DE, Evenson EB, Larson GJ (1999): Glaciological and geological implications of basal-ice accreation in overdeepenings. In: Mickelson DM and Attig JW (eds.) *Glacial Processes. Past and Present.* Geological Society of America, Boulder, USA, 1–9.

Altman D (1994): Fuzzy set theoretic approaches for handling imprecision in spatial analysis. *International Journal of Geographical Information Systems*, 8: 3, 271–289 [10.1080/02693799408902000].

Amgaa T (2003): Wavelet-based Analysis for Object Separation from Laser Altimetry Data. MSc thesis. International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, Netherlands. http://www2.itc.nl/library/Papers_2003/msc/gfm/amgaa_tsolmon.pdf.

ANSI (1998): American National Standards Institute (ANSI) NCITS 320-1998. Draft. Part 2: Spatial Features. http://thor-f5.er.usgs.gov/sdts/ standard/latest_draft/pdf/part2.pdf.

APA (2002): American Psychological Association Ethical Principles of Psychologists and Code of Conduct. http://www.apa.org/ethics/code.

Arrell KE (2002): Is GIS a useful tool for Geomorphologists? *Journal of the Durham University Geographical Society*. Available from: http://www.geog.leeds.ac.uk/fileadmin/downloads/school/people/academic/k.arrell/GeomorphologyAndGIS.pdf.

Art in the Picture (2009): ArtInThePicture.com. An Introduction into Art History. Georges Seurat. http://www.artinthepicture.com/paintings/Georges_Seurat/The-Seine-at-Le-Grande-Jatte.

B

Ball GH and Hall DJ (1965): Isodata, a novel method of data analysis and pattern classification. Technical Report SRI Project 5533. Stanford Research Institute Menlo Park, USA.

Barsch D and Caine N (1984): The nature of mountain geomorphology. *Mountain Research and Development*, 4: 4, 287–298. [cited in Owens and Slaymaker 2004]

Bates RL and Jackson JA (eds., 1990): "Valley", "Valley floor". Glossary of Geology. American Geological Institute, Alexandria, USA.

Beven KJ and Kirkby MJ (1979): A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, 24: 1, 43–69.

Bezdek JC, Ehrlich R and Full W (1984): FCM: The fuzzy c-means clustering algorithm. *Computers & Geosciences*, 10, 191–203 [10.1016/0098-3004(84)90020-7].

BFO (2009): Basic Formal Ontology (BFO). http://www.ifomis.org/bfo/home.

Bills BC and Li G (2005): Correlating homicide and suicide. *International Journal of Epidemiology*, 34: 4, 837–845 [10.1093/ije/dyi079].

Bittner T and Winter S (2004): Geo-semantics and ontology. *Proceedings of the Bentley Empowered Conference*, Orlando, USA, 24–26 May 2004.

Bjørke JT and Nilsen S (2003): Wavelets applied to simplification of digital terrain models. *International Journal of Geographical Information Science*, 17: 7, 601–621 [10.1080/1365881031000135500].

Blaszczynski JS (1997): Landform characterization with geographic information systems. *Photogrammetric Engineering & Remote Sensing*, 63: 2, 183–191.

Blume H (1992): Colour Atlas of the Surface Forms of the Earth. Belhaven Press, London, UK.

Bolongaro-Crevenna A, Torres-Rodríguez V, Sorani V, Frame D and Ortiz MA (2005): Geomorphometric analysis for characterizing landforms in Morelos State, Mexico. *Geomorphology*, 67, 407–422 [10.1016/j.geomorph.2004.11.007].

Brabyn L (1998): GIS analysis of macro landform. In: Firns P (ed.) *SIRC 1998: Towards the Next Decade of Spatial Information Research*. Proceedings of the 10th Annual Colloquium of the Spatial Information Research Centre, 16–19 December 1998, Dunedin, New Zealand, 35–48.

Brasington J and Richards K (1998): Interactions between model predictions, parameters and DTM scales for TOPMODEL. *Computers & Geosciences,* 24: 4, 299–314 [10.1016/S0098-3004(97)00081-2].

Brooks RR, Grewe L and Iyengar SS (2001): Recognition in the wavelet domain: A survey. *Journal of Electronic Imaging*, 10: 3, 757–784 [10.1117/1.1381560].

Brown DG, Lusch DP and Duda KA (1998): Supervised classification of types of glaciated landscapes using digital elevation data. *Geomorphology*, 21, 233–250.

Bruneau P, Gascuel-Odoux C, Robin P, Merot P and Beven K (1995): Sensitivity to space and time resolution of a hydrological model using digital elevation data. *Hydrological Processes*, 9: 1, 69–81 [10.1002/hyp.3360090107].

Bryson B (2003): A Short History of Nearly Everything. Broadway Books, New York, USA.

Burrough PA and McDonnell RA (1998): Principles of Geographical Information Systems. Oxford University Press, Oxford, UK.

Burrough PA, van Gaans PFM and Hootsmans R (1997): Continuous classification in soil survey: Spatial correlation, confusion and boundaries. *Geoderma*, 77: 2–4, 115–135 [10.1016/S0016-7061(97)00018-9].

Burrough PA, van Gaans PFM and MacMillan RA (2000): High-resolution landform classification using fuzzy k-means. *Fuzzy Sets and Systems*, 113: 1, 37–52 [10.1016/S0165-0114(99)00011-1].

Burrough PA, Wilson JP, van Gaans PF and Hansen AJ (2001): Fuzzy k-means classification of topo-climatic data as an aid to forest mapping in the Greater Yellowstone Area, USA. *Landscape Ecology*, 16: 6, 523–546 [10.1023/A:1013167712622].

Büchner G (1839): Lenz. Reprinted and complemented with an English translation by Richard Sieburth in 2004. Archipelago Books, New York, USA. German text freely available from http://gutenberg.spiegel.de/?id=5&xid=261&kapitel=1.

C

Cai G, Wang H and MacEachren AM (2003): Communicating vague spatial concepts in human-GIS interactions: A collaborative dialogue approach. In: Kuhn W, Worboys M and Timpf S (eds.) *Lecture Notes in Computer Science*, 2825, Spatial Information Theory. Foundations of Geographic Information Science. Proceedings of COSIT 2003, 24–28 September 2003, Kartause Ittingen, Switzerland, 287–300 [10.1007/b13481].

Câmara G, Egenhofer MJ, Fonseca F and Monteiro AMV (2001): What's in an image? In: Montello DR (ed.) *Lecture Notes in Computer Science*, 2205, Spatial Information Theory. Foundations of Geographic Information Science. Proceedings of COSIT 2001, 19–23 September 2001, Morro Bay, USA, 474–488 [10.1007/3-540-45424-1_32].

Carabajal CC and Harding DJ (2005): ICESat validation of SRTM C-band digital elevation models. *Geophysical Research Letters*, 32, L22S01 [10.1029/2005GL023957].

Carabajal CC and Harding DJ (2006): SRTM C-band and ICESat laser altimetry elevation comparisons as a function of tree cover and relief. *Photogrammetric Engineering & Remote Sensing*, 72, 287–298.

Carroll R (1983): Automated gully delineation using digital elevation data. ACSM-ASP 49th Annual Meeting, Technical Papers, Washington D.C., USA, 144–151.

Carter JR (1992): The effect of data precision on the calculation of slope and aspect using gridded DEMs. *Cartographica*, 29: 1, 22–34.

Cayley A (1859): On contour and slope lines. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 18, 264–268. Reprinted in: Forsyth AR (ed., 1889) *The Collected Mathematical Papers of Arthur Cayley*, Volume 4, Cambridge University Press, Cambridge, UK, 108–111.

Champagnac JD, Molnar P, Anderson RS, Sue C and Delacou B (2007): Quaternary erosion-induced isostatic rebound in the western Alps. *Geology*, 35, 195–198 [10.1130/G23053A.1].

Chaudhry O and Mackaness W (2007): Automatic identification of hills and ranges using morphometric analysis. In: Winstanley AC (ed.) *Proceedings of the Geographical Information Science Research UK (GISRUK) Conference*, Maynooth, Ireland, 11–13 April 2007, 333–342.

Chaudhry OZ and Mackaness WA (2008): Creating mountains out of mole hills: Automatic identification of hills and ranges using morphometric analysis. *Transactions in GIS*, 12: 5, 567–589 [10.1111/j.1467-9671.2008.01116.x]

Chorley RJ, Schumm SA and Sugden DE (1984): Geomorphology. Methuen & Co., New York, USA.

Chorowicz J, Ichoku C, Riazanoff S, Kim Y and Cervelle B (1992): A combined algorithm for automated drainage network extraction. *Water Resources Research*, 28: 5, 1293–1302.

Church M and Slaymaker O (1989): Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature*, 337: 2, 452–454 [10.1038/337452a0].

Claessens L, Heuvelink GBM, Schoorl JM and Veldkamp A (2005): DEM resolution effects on shallow landslide hazard and soil redistribution modelling. *Earth Surface Processes and Landforms*, 30: 4, 461–477 [10.1002/esp.1155].

Clarke SE, Burnett KM and Miller DJ (2008): Modeling streams and hydrogeomorphic attributes in Oregon from digital and field data. *Journal of the American Water Resources Association*, 44: 2, 459–477 [10.1111/j.1752-1688.2008.00175.x].

Cockbain AE (1980): James Clerk Maxwell, the first quantitative geomorphologist? *Mathematical Geology*, 12: 6, 615–616 [10.1007/BF01034748].

Corripio JG (2003): Vectorial algebra algorithms for calculating terrain parameters from DEMs and solar radiation modelling in mountainous terrain. *International Journal of Geographical Information Science*, 17: 1, 1–23 [10.1080/7138117 44].

Couclelis H (1996): Towards an operational typology of geographic entities with ill-defined boundaries. In: Burrough PA and Frank AU (eds.) *Geographic Objects with Indeterminate Boundaries*, Taylor and Francis, London, UK, 45–56.

CRAN (2009): The Comprehensive R Archive Network, http://cran.r-project.org.

Cronin T (2000): Classifying hills and valleys in digitized terrain. *Photogrammetric Engineering & Remote Sensing*, 66, 1129–1137.

D

Dalrymple JB, Blong RJ and Conacher AJ (1968): A hypothetical nine unit landsurface model. Zeitschrift für Geomorphologie, 12, 60–76. [cited in Pennock et al. 1987]

Darra A, Kavouras M and Tzelepis N (2003): A rational characterization and visualization of topographic relief into mountainous, semi-mountainous and plane terrain. *Proceedings of the 21st International Cartographic Conference*, 10–16 August 2003, Durban, South Africa.

Davies TRH and Korup O (2007): Persistent alluvial fanhead trenching resulting from large, infrequent sediment inputs. *Earth Surface Processes and Landforms*, 32: 5, 725–742 [10.1002/esp.1410].

de Bruin S and Stein A (1998): Soil-landscape modelling using fuzzy c-means clustering of attribute data derived from a Digital Elevation Model (DEM). *Geoderma*, 83: 1–2, 17–33 [10.1016/S0016-7061(97)00143-2].

Dehn M, Gärtner H and Dikau R (2001): Principles of semantic modeling of landform structures. *Computers & Geosciences*, 27: 8, 1005–1010 [10.1016/S0098-3004(00)00138-2].

Demoulin A, Bovy B, Rixhon G and Cornet Y (2007): An automated method to extract fluvial terraces from digital elevation models: The Vesdre valley, a case study in eastern Belgium. *Geomorphology*, 91: 1–2, 51–64 [10.1016/j.geomorph.2007. 01.020].

Deng Y (2007): New trends in digital terrain analysis: Landform definition, representation and classification. Progress in Physical Geography, 31: 4, 405–419 [10.1177/0309133307081291].

Deng YX and Wilson JP (2007): Multi-scale and multi-criteria mapping of mountain peaks as fuzzy entities. *International Journal of Geographical Information Science*, 22: 2, 205–218 [10.1080/13658810701405623].

Deng YX, Wilson JP and Sheng J (2006): Effects of variable attribute weights on landform classification. *Earth Surface Processes and Landforms*, 31: 11, 1452–1462 [10.1002/esp.1401].

Derungs C and Purves RS (2007): Empirical experiments on the nature of Swiss mountains. In: Winstanley AC (ed.) *Proceedings of the Geographical Information Science Research UK (GISRUK) Conference*, Maynooth, Ireland, 11–13 April 2007, 348–352.

Desmet PJJ and Govers G (1996): Comparison of flow routing algorithms for digital elevation models and their implications for predicting ephemeral gullies. *International Journal of Geographical Information Systems*, 10: 3, 311–331.

DGIWG (2000): The Digital Geographic Information Exchange Standard (DIGEST). Part 4: Feature and Attribute Coding Catalogue (FACC). https://www.dgiwg.org/digest/DownloadDigest.htm.

DGIWG (2009): Digital Geographic Information Exchange Standard (DIGEST). https://www.dgiwg.org/digest.

Dikau R (1988): Entwurf einer geomorphographisch-analytischen Systematik von Reliefeinheiten. *Heidelberger Geographische Bausteine*, 5, 1–45.

Dikau R (1989): The application of a digital relief model to landform analysis in geomorphology. In: Raper, J. (ed.) *Three Dimensional Applications in Geographical Information Systems*, Taylor & Francis, London, UK 51–77.

Dobermann A and Oberthür T (1997): Fuzzy mapping of soil fertility – a case study on irrigated riceland in the Philippines. *Geoderma*, 77: 2–4, 317–339 [10.1016/S0016-7061(97)00028-1].

Dobos E, Micheli E, Baumgardner MF, Biehl L and Helt T (2000): Use of combined digital elevation model and satellite radiometric data for regional soil mapping. *Geoderma*, 97: 3–4, 367–391 [10.1016/S0016-7061(00)00046-X].

Drăguţ L and Blaschke T (2006): Automated classification of landform elements using object-based image analysis. *Geomorphology*, 81: 3–4, 330–344 [10.1016/j.geomorph.2006.04.013].

Dowling T, Summerell GK and Walker J (2003): Soil wetness as an indicator of stream salinity: A landscape position index approach. *Environmental Modelling & Software*, 18: 6, 587–593 [10.1016/S1364-8152(03)00034-3].

Dubayah R and Rich PM (1995): Topographic solar radiation models for GIS. *International Journal of Geographical Information Systems*, 9: 4, 405–419 [10.1080/02693799508902046].

Dymond JR, Derose RC and Harmsworth GR (1995): Automated mapping of land components from digital elevation data. *Earth Surface Processes and Landforms*, 20: 2, 131–137 [10.1002/esp.3290200204].

E

Edwards G (1993): The Voronoi model and cultural space: Applications to the social sciences and humanities. In: Frank AU and Campari I (eds.) *Lecture Notes in Computer Science*, 716. Spatial Information Theory. A Theoretical Basis for GIS. Proceedings of COSIT'93, 19–22 September 1993, Marciana Marina, Italy, 202–214 [10.1007/3-540-57207-4].

Egenhofer MJ and Mark DM (1995a): Naive Geography. Report 95-8. National Center for Geographic Information and Analysis, http://www.ncgia.ucsb.edu/Publications/Tech_Reports/95/95-8.pdf.

Egenhofer MJ and Mark DM (1995b): Naive geography. In: Frank AU and Kuhn W (eds.) *Lecture Notes in Computer Science*, 988. Spatial Information Theory. A Theoretical Basis for GIS. Proceedings of COSIT'95, 21–23 September 1995, Semmering, Austria, 1–15.

Encyclopædia Britannica (2009): "Treaty of Tordesillas". Encyclopædia Britannica Online. http://www.britannica.com/EBchecked/topic/599856/Treaty-of-Tordesillas.

ERSDAC (2007): The ASTER G-DEM Project. http://www.ersdac.or.jp/GDEM/E.

Erwig M and Schneider M (1997): Vague regions. In: Lecture Notes in Computer Science, 1262. *Advances in Spatial Databases*. Proceedings of the 5th International Symposium SSD '97, 15–18 July 1997, Berlin, Germany, 298–320.

Etzelmüller B and Sulebak JR (2000): Developments in the use of digital elevation models in periglacial geomorphology and glaciology. In: Maisch M, Vonder Mühll D and Monbaron M (eds.) *Physische Geographie*, 41. Entwicklungstendenzen und Zukunftsperspektiven in der Geomorphologie. Proceedings of Jahrestagung der Schweizerischen Geomorphologischen Gesellschaft, 11–13 October 2000, Winterthur, Switzerland, 35–58.

Evans IS (1972): General geomorphometry, derivatives of altitude, and descriptive statistics. In: Chorley RJ (ed.) *Spatial Analysis in Geomorphology*, Methuen & Co., London, UK, 17–90.

Evans IS (1979): An integrated system of terrain analysis and slope mapping. Report 6 on Grant DA-ERO-591-73-G0040, Statistical characterization of altitude matrices by computer. Department of Geography, University of Durham, UK.

Evans IS (1980): An integrated system of terrain analysis and slope mapping. *Zeitschrift für Geomorphologie, Supplementband*, 36, 274-295.

Evans IS and Cox NJ (1999): Relations between land surface properties: Altitude, slope and curvature. In: Hergarten S and Neugebauer HJ (eds.) *Process Modelling and Landform Evolution. Lecture Notes in Earth Sciences*, 78, Springer Verlag, Berlin, Germany, 13–45.

EXIF (2007): EXIF and related resources, http://www.exif.org.

F

Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L, Seal D, Shaffer S, Shimada J, Umland J, Werner M, Oskin M, Burbank D and Alsdorf D (2007): The Shuttle Radar Topography Mission. *Reviews of Geophysics*, 45, RG2004 [10.1029/2005RG000183].

FEDSIM (1996): The Spatial Data Transfer Standard. Handbook for Technical Staff. A "road map" to the SDTS for technical staff involved in SDTS implementation. Federal Systems Integration and Management Center (FEDSIM). http://thor-f5.er.usgs.gov/sdts/articles/pdf/staff.pdf.

FEDSIM (1997): SDTS. Senior Management Overview. Federal Systems Integration and Management Center (FEDSIM). http://thor-f5.er.usgs.gov/sdts/articles/pdf/senmgr.pdf.

Felicísimo AM (1994): Modelos digitales del terreno: Principios y aplicaciones en las ciencias ambientales. Pentalfa Ediciones, Oviedo, Spain.

Felicísimo AM (1999): Curso introductorio: Modelos digitales del terreno. http://www.etsimo.uniovi.es/~feli. [cited in Bolongaro-Crevenna et al. 2005]

Felicísimo AM (2001): Modelos digitales del terreno – Curso de introducción: Capítulo 4, Descripción y análisis del relieve. http://www.etsimo.uniovi.es/~feli/CursoMDT/Tema_4.pdf.

Fellbaum C (ed., 1998): WordNet: An Electronic Lexical Database. MIT Press, Cambridge.

Fels JE (1995): Landscape Position and Classified Landtype Mapping for the Statewide DRASTIC Mapping Project. North Carolina State University, Raleigh, USA. Technical report to the North Carolina Department of Environment, Health, and Natural Resources, Division of Environmental Management.

Fels JE and Matson KC (1996): A cognitively-based approach for hydrogeomorphic land classification using digital terrain models. In: *Proceedings of the 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling*, Santa Fe, USA, 21–25 January 1996.

Fisher P (2000a): Sorites paradox and vague geographies. *Fuzzy Sets and Systems*, 113: 1, 7–18 [10.1016/S0165-0114(99)00009-3].

Fisher P (2000b): Fuzzy modelling. In: Openshaw S and Abrahart RJ (eds.) *Geocomputation*, Taylor & Francis, London, UK, 161–186.

Fisher P, Wood J and Cheng T (2004): Where is Helvellyn? Fuzziness of multi-scale landscape morphometry. *Transactions of the Institute of British Geographers*, 29: 1, 106–128 [10.1111/j.0020-2754.2004.00117.x].

Fitzsimons SJ and Veit H (2001): Geology and geomorphology of the European Alps and the Southern Alps of New Zealand: A comparison. *Mountain Research and Development*, 21: 4, 340–349 [10.1659/0276-4741(2001)021[0340:GAGOT E]2.0.CO;2]

Fleming MD and Hoffer RM (1979): Machine processing of Landsat MSS data and DMA topographic data for forest cover type mapping. In: *Proceedings of the 1979 Symposium on Machine Processing of Remotely Sensed Data*, West Layfayette, USA, 377–390.

Flood M (2001a): Lidar activities and research priorities in the commercial sector. In: Hofton MA (ed.) *International Archives of Photogrammetry and Remote Sensing*, XXXIV-3/W4. Proceedings of the ISPRS Workshop "Land surface mapping and characterization using laser altimetry", 22–24 October 2001, Annapolis, USA, 3–7.

Flood M (2001b): Laser altimetry: From science to commercial Lidar mapping. *Photogrammetric Engineering & Remote Sensing*, 67: 11, 1209–1218.

Florinsky IV (1998): Combined analysis of digital terrain models and remotely sensed data in landscape investigations. *Progress in Physical Geography*, 22: 1, 33–60 [10.1177/030913339802200102].

Florinksy IV and Kuryakova GA (2000): Determination of grid size for digital terrain modelling in landscape investigations – exemplified by soil moisture distribution at a micro-scale. *International Journal of Geographical Information Science,* 14: 8, 815–832 [10.1080/136588100750022804].

Fowler R (2001): Topographic LIDAR. In: Maune DF (ed.) Digital Elevation Model Technologies and Applications. The DEM Users Manual. ASPRS, Bethesda, USA, 207–226.

Franssen HJWMH, van Eijnsbergen AC and Stein A (1997): Use of spatial prediction techniques and fuzzy classification for mapping soil pollutants. *Geoderma*, 77: 2–4, 243–262 [10.1016/S0016-7061(97)00024-4].

Frary RB (1996): Hints for designing effective questionnaires. *Practical Assessment, Research & Evaluation*, 5: 3, http://PAREonline.net/getvn.asp?v=5&n=3.

Freundschuh SM and Egenhofer MJ (1997): Human conceptions of spaces: Implications for geographic information systems. *Transaction in GIS*, 2: 4, 361–375.

G

Gallant JC and Dowling TI (2003): A multiresolution index of valley bottom flatness for mapping depositional areas. *Water Resources Research*, 39, 1347 [10.1029/2002WR001426].

Gallant JC and Hutchinson MF (1996): Towards an understanding of landscape scale and structure. In: *Proceedings of the 3rd International Workshop/Conference on Integrating GIS and Environmental Modelling*, 21–26 January 1996, Santa Fe, USA. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/gallant_john/paper.html.

Gallant JC and Wilson JP (1996): TAPES-G: A grid-based terrain analysis program for the environmental sciences. *Computers & Geosciences*, 22: 7, 713–722 [10.1016/0098-3004(96)00002-7].

Gao J (1997): Resolution and accuracy of terrain representation by grid DEMs at a micro-scale. *International Journal of Geographical Information Science*, 11: 2, 199–212 [10.1080/136588197242464].

Gärling T and Golledge RG (1989): Environmental perception and cognition. In: Zube EH and Moore GT (eds.) *Advances in Environment, Behavior, and Design*, Plenum Publishing, New York, USA, 203–236.

Gauss CF (1827): Disquisitiones generales circa area superficies curvas. *Commentationes Societatis Regiae Scientiarum Gottingensis Recentiores*, 6, 99–146 (obtainable from: http://gdz.sub.uni-goettingen.de/dms/load/img/?IDDOC=2339 99). [cited in Shary et al. 2002]

Geoinformation Office of the Canton of Bern (s.a.): Amt für Geoinformation, http://www.bve.be.ch/site/index/agi.

Geomorphometry (2009): geomorphometry.org: The science of digital terrain analysis, http://geomorphometry.org.

Giles PT (1998): Geomorphological signatures: classification of aggregated slope unit objects from digital elevation and remote sensing data. *Earth Surface Processes and Landforms*, 23: 7, 581–594 [10.1002/(SICI)1096-9837(199807)23: 7<581::AID-ESP863>3.0.CO;2-S].

Giles PT and Franklin SE (1998): An automated approach to the classification of the slope units using digital data. *Geomorphology*, 21: 3–4, 251–264 [10.1016/S0169-555X(97)00064-0].

Goldstein L (2000): How to boil a live frog. *Analysis*, 60: 266, 171–177 [10.1111/1467-8284.00220].

Google Earth (2009): Google Earth version 5. http://earth.google.com.

Greatbatch I, Wood J and Fisher P (2007): A comparison of morphometric and web prominence of mountain features. In: Winstanley AC (ed.) *Proceedings of the Geographical Information Science Research UK (GISRUK) Conference*, Maynooth, Ireland, 11–13 April 2007, 312–317.

Greenacre MJ (2007): Interdisciplinary Statistics. Correspondence Analysis in Practice. Chapman & Hall / CRC, Boca Raton, USA.

Grigg D (1967): Regions, models and classes. In: ChorleyRJ and Haggett P (eds.) Models in Geography, Methuen & Co., London, UK, 461–509.

Gruber TR (1993): A translation approach to portable ontology specifications. *Knowledge Acquisition*, 5: 2, 199–220.

Guarino N (1998): Formal ontology and information systems. In: Guarino N (ed.) *Formal Ontology in Information Systems*. Proceedings of FOIS'98, Trento, Italy, 6–8 June 1998, 3–15.

Guth PL (1995): Slope and aspect calculations on gridded digital elevation models: Examples from a geomorphometric toolbox for personal computers. *Zeitschrift für Geomorphologie, Supplementband*, 101, 31–52.

H

Hammond EH (1954): Small-scale continental landform maps. *Annals of the Association of American Geographers*, 44: 1, 33–42.

Hayes PJ (1979): The naive physics manifesto. In: Michie D (ed.) *Expert Systems in the Micro-electronic Age. Papers of the 1979 AISB Summer School.* Edinburgh University Press, Edinburgh, UK, 242–270.

Hengl T (2006): Finding the right pixel size. *Computers & Geosciences*, 32: 9, 1283–1298 [10.1016/j.cageo.2005.11.008].

Hengl T and Reuter HI (eds., 2009): Geomorphometry. Concepts, Software, Applications. Elsevier, Amsterdam, Netherlands.

Hengl T and Rossiter DG (2003): Supervised landform classification to enhance and replace photo-interpretation in semi-detailed soil survey. *Soil Science Society of America Journal*, 67, 1810–1822.

Hengl T, Gruber S and Shrestha DP (2003): Digital Terrain Analysis in ILWIS. Lecture Notes and User Guide. International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, Netherlands, http://www.itc.nl/library/ Papers_2003/misca/hengl_digital.pdf.

Hengl T, Gruber S and Shrestha DP (2004): Reduction of errors in digital terrain parameters used in soil-landscape modelling. *International Journal of Applied Earth Observation and Geoinformation*, 5: 2, 97–112 [10.1016/j.jag.2004.01.006].

Hewitt AE (1992): Soil classification in New Zealand: Legacy and lessons. *Australian Journal of Soil Research*, 30: 6, 843–854 [10.1071/SR9920843].

Hinderer M (2001): Late Quaternary denudation of the Alps, valley and lake fillings and modern river loads. *Geodinamica Acta*, 14: 4, 231–263 [10.1016/S0985-3111(01)01070-1].

Hofton M, Dubayah R, Blair JB and Rabine D (2006): Validation of SRTM elevations over vegetated and non-vegetated terrain using medium footprint LiDAR. *Photogrammetric Engineering & Remote Sensing*, 72, 279–285.

Holmstrand P (2009): Map multiple locations by address, http://www.batchgeocode.com.

Horn BKP (1981): Hill shading and the reflectance map. *Proceedings of the IEEE*, 69: 1, 14–47.

Hugentobler M (2004): Terrain Modelling with Triangle Based Free-Form Surfaces. PhD thesis, University of Zurich, Switzerland.

Huggett RJ (1975): Soil landscape systems: A model of soil genesis. *Geoderma*, 13: 1, 1–22 [10.1016/0016-7061(75)90035-X].

Huggett RJ (2007): Fundamentals of Geomorphology. Routledge, London, UK.

Huuse M and Lykke-Andersen H (2000): Overdeepened Quaternary valleys in the eastern Danish North Sea: Morphology and origin. *Quaternary Science Reviews*, 19: 12, 1233–1253 [10.1016/S0277-3791(99)00103-1].

I

IEEE SUO Working Group (2003): Standard Upper Ontology Working Group, http://suo.ieee.org.

Internet Archive (s.a.): Internet Archive, http://www.archive.org.

Irvin BJ, Ventura SJ and Slater BK (1995): Landform classification for soil-landscape studies. In: *Proceedings of the 15th ESRI User Conference*, Palm Springs, USA, 22–26 May 1995.

Irvin BJ, Ventura SJ and Slater BK (1997): Fuzzy and isodata classification of landform elements from digital terrain data in Pleasant Valley, Wisconsin. *Geoderma*, 77: 2–4, 137–154 [10.1016/S0016-7061(97)00019-0].

Ittelson WH (1973): Environment perception and contemporary perceptual theory. In: Ittelson WH (ed.) *Environment and Cognition*, Seminar, New York, USA, 1–19.

Iwahashi J and Pike RJ (2007): Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature. *Geomorphology*, 86: 3–4, 409–440 [10.1016/j.geomorph.2006.09.012].

J

Jain AK, Murty MN and Flynn PJ (1999): Data clustering: A review. *ACM Computing Surveys*, 31: 3, 264–323.

Jarvis A, Reuter HI, Nelson A, Guevara E (2006): Hole-filled seamless SRTM data version 3, International Centre for Tropical Agriculture (CIAT), http://srtm.csi.cgiar.org.

Jenny H (1994): Factors of Soil Formation. Dover Publications, New York, USA.

Jenson S and Domingue JO (1988): Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering & Remote Sensing*, 54: 11, 1593–1600.

Jones KH (1998): A comparison of algorithms used to compute hill slope as a property of the DEM. *Computers & Geosciences*, 24: 4, 315–323 [10.1016/S0098-3004(98)00032-6].

Jones CB and Purves RS (2008): Geographic information retrieval. *International Journal of Geographical Information Science*, 22: 3, 219–228 [10.1080/13658810701626343].

Jones CB, Purves R, Ruas A, Sanderson M, Sester M, van Kreveld M and Weibel R (2002): Spatial information retrieval and geographical ontologies. An overview of the SPIRIT project. In: *Proceedings of the 25th ACM SIGIR conference on Research and Development in Information Retrieval*, 11–15 August 2002, Tampere, Finland, 387–388 [10.1145/5643 76.564457].

Jones CB, Purves RS, Clough PD and Joho H (2008): Modelling Vague Places with Knowledge from the Web. *International Journal of Geographic Information Science*, 22: 10, 1045–1065 [10.1080/13658810701850547].

K

Kasai M, Marutani T and Brierley GJ (2004): Patterns of sediment slug translation and dispersion following typhoon-induced disturbance, Oyabu Creek, Kyushu, Japan. *Earth Surface Processes and Landforms*, 29: 1, 59–76 [10.1002/esp.1013].

Kearey P (2001): The New Penguin Dictionary of Geology. Penguin Books, London, UK.

Kienzle SW (2004): The effect of DEM raster resolution on first order, second order and compound terrain derivatives. *Transactions in GIS*, 8: 1, 83–111 [10.1111/j.1467-9671.2004.00169.x].

Klingseisen B, Metternicht G and Paulus G (2008): Geomorphometric landscape analysis using a semi-automated GIS-approach. *Environmental Modelling & Software*, 23: 1, 109–121 [10.1016/j.envsoft.2007.05.007].

Koppes M and Hallet B (2006): Erosion rates during deglaciation in Icy Bay, Alaska. *Journal of Geophysical Research*, 111, F02023 [10.1029/2005JF000349].

Korup O and Schlunegger F (2009): Rock type control on erosion-induced uplift in the eastern Swiss Alps. *Earth and Planetary Science Letters*, 278: 3–4, 278–285 [10.1016/j.epsl.2008.12.012].

Korup O and Tweed F (2007): Ice, moraine, and landslide dams in mountainous terrain. *Quaternary Science Reviews*, 26: 25–28, 3406–3422 [10.1016/j.quascirev.2007.10.012].

Kovacs K, Dolbear C and Goodwin J (2007): Spatial concepts and OWL issues in a topographic ontology framework. In: Winstanley AC (ed.) *Proceedings of the Geographical Information Science Research UK (GISRUK) Conference*, Maynooth, Ireland, 11–13 April 2007, 88–92.

Krcho J (1973): Morphometric analysis of relief on the basis of geometric aspect of field theory. *Acta Geographica Universitatis Comenianae, Geographico-Physica*, 1, 7–233. [cited in Mitasova and Hofierka 1993]

Krcho J (1991): Georelief as a subsystem of landscape and the influence of morphometric parameters of georelief on spatial differentiation of landscape-ecological processes. *Ekológia/Ecology (CSFR)*, 10: 2, 115–157. [cited in Mitasova and Hofierka 1993]

Kuhlemann J, Frisch W, Székely B, Dunkl I and Kázmér M (2002): Post-collisional sediment budget history of the Alps: Tectonic versus climatic control. *International Journal of Earth Sciences*, 91: 5, 818–837 [10.1007/s00531-002-026 6-y].

Kwan M-P (2000): Interactive geovisualization of activity-travel patterns using three-dimensional geographical information systems: A methodological exploration with a large data set. *Transportation Research Part C: Emerging Technologies*, 8: 1–6, 185-203.

Kwan M-P and Lee J (2004): Geovisualization of human activity patterns using 3D GIS: A time-geographic approach. In: Goodchild MF and Janelle DG (eds.) *Spatially Integrated Social Science: Examples in Best Practice*. Oxford University Press, New York, USA, 48–66 (colour figures obtainable from http://www.csiss.org/best-practices/siss/ 03).

L

Lakoff G (1987): Women, Fire, and Dangerous Things. What Categories Reveal about the Mind. The University of Chicago Press, Chicago, USA.

Lancaster ST and Casebeer NE (2007): Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes. *Geology*, 35: 11, 1027–1030 [10.1130/G239365A.1].

LandSerf (s.a.): LandSerf, http://www.landserf.org.

Lane SN, Brookes CJ, Kirkby MJ and Holden J (2004): A network-index-based version of TOPMODEL for use with high-resolution digital topographic data. *Hydrological Processes*, 18: 1, 191–201 [10.1002/hyp.5208].

LAO (2009): Laboratory for Applied Ontology (LAO). DOLCE: a Descriptive Ontology for Linguistic and Cognitive Engineering. http://www.loa-cnr.it/DOLCE.html

Lapidus DF, Coates DR, Winstanley I, MacDonald J and Burton C (2003): Collins Dictionary of Geology. HarperCollins Publishers, Glasgow, UK.

Larson RR (1996): Geographic information retrieval and spatial browsing. In: Smith LC and Gluck M (eds.) *Geographic Information Systems and Libraries: Patrons, Maps, and Spatial Information*. Proceedings of the 32nd Clinic on Library Applications of Data Processing, 10–12 April 1995, Urbana-Champaign, USA, 81–124.

Legendre P and Legendre L (1998): Numerical Ecology, Developments in Environmental Modelling 20, Elsevier, Amsterdam, Netherlands.

LeVeque RJ (2005): Finite Difference Methods for Differential Equations. Course Notes. University of Washington, USA, http://www.amath.washington.edu/~rjl/pubs/am58X/amath58X05.pdf.

Li Z, Zhu Q and Gold C (2005): Digital Terrain Modeling. Principles and Methodology. CRC Press, Boca Raton, USA.

Longley PA, Goodchild MF, Maguire DJ and Rhind DW (2001): Geographic Information Systems and Science. John Wiley & Sons, Chichester, UK.

Lu H, Moran CJ and Sivapalan M (2005): A theoretical exploration of catchment-scale sediment delivery. *Water Resources Research*, 41, W09415 [10.1029/2005WR004018].

M

MacMillan RA, Pettapiece WW, Nolan S and Goddard TW (2000): A generic procedure for automatically segmenting landforms into landform elements using DEMs, heuristic rules and fuzzy logic. *Fuzzy Sets and Systems*, 113: 1, 81–109 [10.1016/S0165-0114(99)00014-7].

Mahler E (2001): Scale-Dependent Filtering of High Resolution Digital Terrain Models in the Wavelet Domain. MSc thesis. University of Zurich, Switzerland.

Mark DM (1975): Geomorphometric parameters: A review and evaluation. *Geografiska Annaler. Series A, Physical Geography*, 57: 3–4, 165–177.

Mark DM (1993): Toward a theoretical framework for geographic entity types. In: Frank AU and Campari I (eds.) *Lecture Notes in Computer Science*, 716. Spatial Information Theory. A Theoretical Basis for GIS. Proceedings of COSIT'93, 19–22 September 1993, Marciana Marina, Italy, 270–283 [10.1007/3-540-57207-4].

Mark DM and Church M (1977): On the misuse of regression in earth science. *Mathematical Geology*, 9: 1, 63–75 [10.1007/BF02312496].

Mark D and Sinha G (2006): Ontology of landforms: Delimitation and classification of topographic eminences. In: Raubal M, Miller HJ, Frank AU, Goodchild MF (eds.) *Proceedings of the 4th International Conference on Geographic Information Science*, extended abstracts, Münster, Germany, 20–23 September 2006, 129–132.

Mark DM and Smith B (2004): A science of topography: From qualitative ontology to digital representations. In: Bishop MP and Shroder Jr JF (eds.) *Geographic Information Science and Mountain Geomorphology*, Springer Verlag, Berlin, Germany, 75–100.

Mark DM and Turk AG (2003): Landscape categories in Yindjibarndi: Ontology, environment, and language. In: Kuhn W, Worboys M and Timpf S (eds.) *Lecture Notes in Computer Science*, 2825, Spatial Information Theory. Foundations of Geographic Information Science. Proceedings of COSIT 2003, 24–28 September 2003, Kartause Ittingen, Switzerland, 31–49 [10.1007/b13481].

Mark DM and Warntz W (1982): James Clerk Maxwell, the first quantitative geomorphologist? Discussion. *Mathematical Geology*, 14: 2, 195–197 [10.1007/BF01083952].

Mark DM, Smith B and Tversky B (1999): Ontology and geographic objects: An empirical study of cognitive categorization. In: Freksa C and Mark DM (eds.) *Lecture Notes in Computer Science*, 1661, Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science. Proceedings of COSIT'99, 25–29 August 1999, Stade, Germany, 283–298.

Martin DW (1996): Doing Psychological Experiments. Brooks/Cole, Pacific Grove, USA.

Martinoni D (2002): Models and Experiments for Quality Handling in Digital Terrain Modelling. PhD thesis. University of Zurich, Switzerland, http://www.geo.uzh.ch/fileadmin/files/content/abteilungen/gis/research/phd_theses/thesis_DariaMartinoni_2002.pdf.

Matson KC and Fels JE (1996): Approaches to automated water table mapping. In: *Proceedings of the 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling*, Santa Fe, USA, 21–25 January 1996.

Maxwell JC (1870): On Hills and Dales. *The Philosophical Magazine and Journal*, 2: 30. Reprinted in: Niven WD (ed., 1965) *The Scientific Papers of James Clerk Maxwell*, Dover Publications, New York, USA, 233–240.

Mayhew S (2004): A Dictionary of Geography. Oxford Reference Online. Oxford University Press. http://www.oxford reference.com/views/BOOK_SEARCH.html?book=t15.

McArdle BH (1988): The structural relationship: Regression in biology. *Canadian Journal of Zoology*, 66: 11, 2329–233 9[10.1139/z88-348].

McBratney AB (1992): On variation, uncertainty and informatics in environmental soil management. *Australian Journal of Soil Research*, 30: 6, 913–935 [10.1071/SR9920913].

McBratney AB (1994): Allocation of new individuals to continuous soil classes. *Australian Journal of Soil Research*, 32: 4, 623–633 [10.1071/SR9940623].

McBratney AB and de Gruijter JJ (1992): A continuum approach to soil classification by modified fuzzy k-means with extragrades. *European Journal of Soil Science*, 43: 1, 159–175 [10.1111/j.1365-2389.1992.tb00127.x].

McBratney AB and Odeh IOA (1997): Application of fuzzy sets in soil science: fuzzy logic, fuzzy measurements and fuzzy decision. *Geoderma*, 77: 2–4, 85–113 [10.1016/S0016-7061(97)00017-7].

McBratney AB, de Gruijter JJ and Brus DJ (1992): Spacial prediction and mapping of continuous soil classes. *Geoderma*, 54: 1–4, 39–64 [10.1016/0016-7061(92)90097-Q].

McCauley RN (1987): The role of theories in a theory of concepts. In: Neisser U (ed.) Concepts and Conceptual Development: Ecological and Intellectual Factors in Categorization. Cambridge University Press, Cambridge, USA, 288–310.

McGraw-Hill Dictionary of Earth Science (2003): McGraw-Hill Dictionary of Earth Science. McGraw-Hill, New York, USA.

McKillop (1998): A Dictionary of Celtic Mythology. Oxford Reference Online. Oxford University Press. http://www.ox fordreference.com/views/BOOK_SEARCH.html?book=t70.

Merriam-Webster Dictionary (2010): "Universe of discourse". http://www.merriam-webster.com/dictionary/universe of discourse.

Mervis CB and Rosch E (1981): Categorization of natural objects. *Annual Review of Psychology*, 32, 89–115 [10.1146/an nurev.ps.32.020181.000513].

Metternicht G, Klingseisen B and Paulus G (2005): A semi-automated approach for GIS based generation of topographic attributes for landform classification. In: *Proceedings of the XXII International Cartographic Conference (ICC2005)*, Coruna, Spain, 11–16 July 2005.

Miliaresis GC (2006): Geomorphometric mapping of asia minor from GLOBE digital elevation model. *Geografiska Annaler, Series A, Physical Geography*, 88: 3, 209–221 [10.1111/j.1468-0459.2006.00296.x].

Miliaresis GC and Argialas DP (1999): Segmentation of physiographic features from the global digital elevation model/ GTOPO30. *Computers & Geosciences*, 25: 7, 715–728 [10.1016/S0098-3004(99)00025-4].

Miliaresis GC and Argialas DP (2002): Quantitative representation of mountain objects extracted from the global digital elevation model (GTOPO30). *International Journal of Remote Sensing*, 23: 5, 949–964 [10.1080/0143116011007 0690].

Miller GA (1995): WordNet: A lexical database for English. *Communications of the ACM*, 38: 11, 39–41.

Milne G (1936): A provisional soil map of East Africa (Kenya, Uganda, Tanganyika, and Zanzibar). East African Agriculture Research Station, Amanin Memoirs, 1–34. [cited in Huggett 1975]

Mitasova H and Hofierka J (1993): Interpolation by regularized spline with tension: II. Application to terrain modeling and surface geometry analysis. *Mathematical Geology*, 25: 6, 657–669 [10.1007/BF00893172]

Möller M, Volk M, Friedrich K and Lymburner L (2008): Placing soil-genesis and transport processes into a landscape context: A multiscale terrain analysis approach. *Journal of Plant Nutrition and Soil Science*, 171: 3, 419–430 [10. 1002/jpln.200625039].

Montello DR (1993): Scale and multiple psychologies of space. In: Frank AU and Campari I (eds.) *Lecture Notes in Computer Science*, 716. Spatial Information Theory. A Theoretical Basis for GIS. Proceeding of COSIT'93, 19–22 September 1993, Marciana Marina, Italy, 312–321.

Montello DR, Goodchild MF, Gottsegen J and Fohl P (2003): Where's downtown? Behavioral methods for determining referents of vague spatial queries. *Spatial Cognition & Computation*, 3: 2–3, 185–204 [10.1207/S15427633SCC0 32&3_06].

Montello DR and Sutton PC (2006): An Introduction to Scientific Research Methods in Geography. Sage, Thousand Oaks, USA.

Moore ID and Burch GJ (1986): Physical basis of the length-slope factor in the Universal Soil Loss Equation. *Soil Science Society of America Journal*, 50, 1294–1298.

Moore ID and Wilson JP (1992): Length-slope factors for the Revised Universal Soil Loss Equation: Simplified method of estimation. *Journal of Soil and Water Conservation*, 47: 5, 423–428.

Moore ID, Grayson RB, Ladson AR (1991): Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. Hydrological Processes, 5, 3–30 [10.1002/hyp.3360050103].

Moore ID, Gessler PE, Nielsen GA and Peterson GA (1993a): Soil attribute prediction using terrain analysis. *Soil Science Society of America Journal*, 57, 443–452.

Moore ID, Gessler PE, Nielsen GA and Peterson GA (1993b): Terrain analysis for soil specific crop management. In: Robert PC, Rust RC and Larson WE (eds.) *Proceedings of the 1st Workshop on Soil Specific Crop Management*, 27–55.

Moreno M, Levachkine S, Torres M and Quintero R (2004): Landform classification in raster geo-images. *Lecture Notes in Computer Science*, 3287, Progress in Pattern Recognition, Image Analysis and Applications. Proceedings of the 9th Iberoamerican Congress on Pattern Recognition (CIARP), Puebla, Mexico, 26–29 October 2004, 558–565 [10.1007/ b101756].

Morgan JM and Lesh AM (2005): Developing landform maps using ESRI's ModelBuilder. In: *Proceedings of the 25th Annual ESRI User Conference*, 25–29 July 2005, San Diego, USA.

Murphy B, Vaze J, Teng J, Tuteja NK, Gallant J, Summerell G, Young J and Wild J (2005): Modelling landscapes using terrain analysis to delineate landforms and predict soil depths – Examples from catchments in NSW. In: Zerger A and Argent RM (eds.) *Proceedings of the International Congress on Modelling and Simulation (MODSIM 2005)*, December 2005, 1423-1429.

MWG (2009): Metadata Working Group, http://www.metadataworkinggroup.org.

N

Nagelschmidt Rodrigues A, Barrera J, de Alencar Lotufo R and Hirata Jr. R (1997): A Tutorial on Mathematical Morphology. http://www.dca.fee.unicamp.br/projects/khoros/mmach/tutor/util/fast.html.

Nichols D (2004): Ontology of Geography. http://sigmakee.cvs.sourceforge.net/*checkout*/sigmakee/KBs/Geography.kif.

Niles I and Pease A (2001): Towards a standard upper ontology. In: Welty C and Smith B (eds.) *Proceedings of the 2nd International Conference on Formal Ontology in Information Systems (FOIS-2001)*, Ogunquit, USA, 17–19 October 2001, 2–9 [10.1145/505168.505170].

Noman NS, Nelson EJ and Zundel AK (2001): Review of automated flood plain delineation from digital terrain models. *Journal of Water Resources Planning and Management*, 127: 6, 394–402 [10.1061/(ASCE)0733-9496(2001)127: 6(394)].

Noman NS, Nelson EJ and Zundel AK (2003): Improved process for floodplain delineation from digital terrain models. *Journal of Water Resources Planning and Management*, 129: 5, 427–436 [10.1061/(ASCE)0733-9496(2003)129: 5(427)].

O

O'Callaghan JF and Mark DM (1984): The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and Image Processing*, 28: 3, 323–344.

Odeh IOA, Chittleborough DJ and McBratney AB (1991): Elucidation of soil-landform interrelationships by canonical ordination analysis. *Geoderma*, 49: 1–2, 1–32 [10.1016/0016-7061(91)90089-C].

Odeh IOA, McBratney AB and Chittleborough DJ (1992): Soil pattern recognition with fuzzy-c-means: Application to classification and soil-landform interrelationships. *Soil Science Society of America Journal*, 56: 2, 505–516.

OED (2009): Oxford English Dictionary: The definitive record of the English language, http://dictionary.oed.com.

Olaya V (2009): Basic land-surface parameters. In: Hengl T and Reuter HI (eds.) Geomorphometry. Concepts, Software, Applications. Elsevier, Amsterdam, Netherlands.

Oliver MA and Webster R (1986): Semi-variograms for modelling the spatial pattern of landform and soil properties. *Earth Surface Processes and Landforms*, 11: 5, 491–504 [10.1002/esp.3290110504].

Ordnance Survey (2009): Ordnance Survey Ontologies, http://www.ordnancesurvey.co.uk/oswebsite/ontology

Owens PN and Slaymaker O (2004):An Introduction to Mountain Geomorphology. In: Owens PN and Slaymaker O (eds.) *Mountain Geomorphology*, Arnold, London, UK, 3–29.

P

Park SJ and van de Giesen N (2004): Soil-landscape delineation to define spatial sampling domains for hillslope hydrology. *Journal of Hydrology*, 295: 1–4, 28–46 [10.1016/j.jhydrol.2004.02.022].

Penninga F (2008): 3D Topography. A Simplical Complex-based Solution in a Spatial DBMS. PhD thesis, Delft University of Technology, Delft, Netherlands, http://www.ncg.knaw.nl/eng/publications/Geodesy/66Penninga.html.

Pennock DJ (2003): Terrain attributes, landform segmentation, and soil redistribution. *Soil & Tillage Research*, 69: 1–2, 15–26 [10.1016/S0167-1987(02)00125-3].

Pennock DJ and Corre MD (2001): Development and application of landform segmentation procedures. *Soil & Tillage Research*, 58: 3–4, 151–162 [10.1016/S0167-1987(00)00165-3].

Pennock DJ, Zebarth BJ and De Jong E (1987): Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. *Geoderma*, 40: 3–4, 297–315 [10.1016/0016-7061(87)90040-1].

Pennock DJ, Anderson DW and de Jong E (1994): Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. *Geoderma*, 64: 1–2, 1–19 [10.1016/0016-7061(94)90086-8].

Phillips EM and Pugh DS (2000): How To Get a PhD. Open University Press, Maidenhead, UK.

PHP (2009): PHP: Hypertext Processor, http://www.php.net.

PhPMyAdmin (2009): phpMyAdmin, http://www.phpmyadmin.net.

Picasa (2009): Picasa version 3. http://picasa.google.com.

Pike RJ (1988): The geometric signature – Quantifying landslide-terrain types from digital elevation models. *Mathematical Geology*, 20: 5, 491–511 [10.1007/BF00890333].

Pike RJ (1995): Geomorphometry – Progress, Practice and Prospect. *Zeitschrift für Geomorphologie, Supplementband*, 101, 221–238.

Pike RJ (2000a): Nano-metrology and terrain modelling – convergent practice in surface characterisation. *Tribology International*, 33: 9, 593–600 [10.1016/S0301-679X(00)00075-X].

Pike RJ (2000b): Geomorphometry – diversity in quantitative surface analysis. *Progress in Physical Geography*, 24: 1, 1–20 [10.1177/030913330002400101].

Pike RJ (2001a): Digital terrain modelling and industrial surface metrology – Converging crafts. *International Journal of Machine Tools & Manufacture*, 41: 13–14, 1881–1888 [10.1016/S0890-6955(01)00052-9].

Pike RJ (2001b): Digital terrain modeling and industrial surface metrology: Converging realms. *Professional Geographer*, 53: 2, 263–274 [10.1111/0033-0124.00284].

Pike RJ (2002): A bibliography of terrain modeling (geomorphometry), the quantitative representation of topography – Supplement 4.0. Open-File Report 02-465. U.S. Department of the Interior and U.S. Geological Survey, http://wrgis.wr.usgs.gov/open-file/of02-465.

Purves R and Jones C (2006): Geographic Information Retrieval (GIR). *Computers, Environment and Urban Systems*, 30: 4, 357–377 [10.1016/j.compenvurbsys.2005.12.001].

Purves RS and Korup O (2007): Multiscale analysis of hillslope height for geomorphometry. In: Winstanley AC (ed.) *Proceedings of the Geographical Information Science Research UK (GISRUK) Conference*, 11–13 April 2007, Maynooth, Ireland, 484–488.

Purves RS, Clough P, Jones CB, Arampatzis A, Bucher B, Finch D, Fu G, Joho H, Syed AK, Vaid S and Yang B (2007): The design and implementation of SPIRIT: A spatially aware search engine for information retrieval on the internet. *International Journal of Geographical Information Science*, 21: 7, 717–745 [10.1080/13658810601169840].

Q

Quinn P, Beven K, Chevallier P and Planchon O (1991): The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes*, 5: 1, 59–79 [10.1002/hyp.3360050106].

Quinn PF, Beven KJ and Lamb R (1995): Then ln(a/tan beta) index: How to calculate it and how to use it within the TOPMODEL framework. *Hydrological Processes*, 9: 2, 161–182 [10.1002/hyp.3360090204].

R

Reuter HI, Wendroth O and Kersebaum KC (2006): Optimisation of relief classification for different levels of generalisation. *Geomorphology*, 77: 1–2, 79–89 [10.1016/j.geomorph.2006.01.001].

Rice RJ (1988): Fundamentals of Geomorphology. Longman Scientific & Technical, Harlow, UK.

Richards KS (1981): Introduction to morphometry. In: Goudie AS (ed.) *Geomorphological Techniques*, Allen & Unwin, London, UK, 25–30.

Richards JA (1993): Remote Sensing Digital Image Analysis: An Introduction. Springer Verlag, Berlin, Germany.

Ritter P (1987): A vector-based slope and aspect generation algorithm. *Photogrammetric Engineering & Remote Sensing*, 53, 1109–1111.

Robinson VB (1988): Some implications of fuzzy set theory applied to geographic databases. *Computers, Environment and Urban Systems*, 12: 2, 89–97 [10.1016/0198-9715(88)90012-9].

Robinson VB (2000): Individual and multipersonal fuzzy spatial relations acquired using human-machine interaction. *Fuzzy Sets and Systems*, 113: 1, 133–145 [10.1016/S0165-0114(99)00017-2].

Romstad B (2001): Improving relief classification with contextual merging. In: Bjørke JT and Tveite H (eds.) *Proceedings of the 8th Scandinavian Research Conference on Geographical Information Science (ScanGIS 2001)*, 25–27 June 2001, Ås, Norway, 3–13.

Rosch E (1978): Principles of categorization. In: Rosch E and Lloyd BB (eds.) Cognition and Categorization. Erlbaum, Hillsdale, USA, 27–48. Available from: http://commonweb.unifr.ch/artsdean/pub/gestens/f/as/files/4610/9778_083247.pdf.

Ruhe RV (1960): Elements of the soil landscape. In: *Transactions of the 7th International Congress of Soil Science*, International Society of Soil Science, Madison, USA, 165–170. [cited in Pennock et al. 1987]

S

Sagar BSD, Murthy MBR, Rao CB and Raj B (2003): Morphological approach to extract ridge and valley connectivity networks from Digital Elevation Models. *International Journal of Remote Sensing*, 24: 3, 573–581 [10.1080/0143 1160304983].

Saulnier G-M, Obled C and Beven K (1997): Analytical compensation between DTM grid resolution and effective values of saturated hydraulic conductivity within the TOPMODEL framework. *Hydrological Processes*, 11: 9, 1331–1346 [10.1002/(SICI)1099-1085(199707)11:9<1331::AID-HYP563>3.0.CO;2-9].

Schaefer FK (1953): Exceptionalism in geography: A methodological examination. *Annals of the Association of American Geographers*, 43: 3, 226–249.

Schmidt J and Andrew R (2005): Multi-scale landform characterization. *Area*, 37: 3, 341–350 [10.1111/j.1475-4762.200 5.00638.x].

Schmidt J and Hewitt A (2004): Fuzzy land element classification from DTMs based on geometry and terrain position. *Geoderma*, 121: 3–4, 243–256 [10.1016/j.geoderma.2003.10.008].

Schmidt J, Evans I and Brinkmann J (2003): Comparison of polynomial models for land surface curvature calculation. *International Journal of Geographical Information Science*, 17: 8, 797–814 [10.1080/13658810310001596058].

Schneider B (2001a): On the uncertainty of local shape of lines and surfaces. *Cartography and Geographic Information Science*, 28: 4, 237–247 [10.1559/152304001782152991].

Schneider B (2001b): Phenomenon-based specification of the digital representation of terrain surfaces. *Transactions in GIS*, 5: 1, 39–52 [10.1111/1467-9671.00066].

Schrott L, Hufschmidt G, Hankammer M, Hofmann T and Dikau R (2003): Spatial distribution of sediment storage types and quantification of valley fill deposits in an alpine basin, Reintal, Bavarian Alps, Germany. *Geomorphology*, 55: 1–4, 45–63 [10.1016/S0169-555X(03)00131-4].

Schuurmann N (2006): Formalization matters: Critical GIS and ontology research. *Annals of the Association of American Geographers*, 96: 4, 726–739 [10.1111/j.1467-8306.2006.00513.x].

Schweizerische Geotechnische Kommission (1963–1967): Geotechnische Karte der Schweiz. 2nd edition, four map sheets 1:200,000. Kümmerly & Frey, Bern, Switzerland.

Scott AT and Pinter N (2003): Extraction of coastal terraces and shoreline-angle elevations from digital terrain models, Santa Cruz and Anacapa Islands, California. *Physical Geography*, 24: 4, 271–294 [10.2747/0272-3646.24.4.271].

Scull P, Franklin J, Chadwick OA and McArthur D (2003): Predictive soil mapping: a review. *Progress in Physical Geography*, 27: 2, 171–197 [10.1191/0309133303pp366ra].

Scull P, Franklin J and Chadwick OA (2005): The application of classification tree analysis to soil type prediction in a desert landscape. *Ecological Modelling*, 181: 1, 1–15 [10.1016/j.ecolmodel.2004.06.036].

Sharpnack DA and Akin G (1969): An algorithm for computing slope and aspect from elevation. *Photogrammetric Engineering & Remote Sensing*, 35, 247–248.

Shary PA (1995): Land surface in gravity points classification by a complete system of curvatures. *Mathematical Geology*, 27: 3, 373–390 [10.1007/BF02084608].

Shary PA, Sharaya LS and Mitusov AV (2002): Fundamental quantitative methods of land surface analysis. *Geoderma*, 107: 1–2, 1–32 [10.1016/S0016-7061(01)00136-7].

Shortridge A (2006): Shuttle Radar Topography Mission elevation data and its relationship to land cover. *Cartography and Geographic Information Science*, 33: 1, 65–75 [10.1559/152304006777323172].

Sigala N, Gabbiani F and Logothetis NK (2002): Visual categorization and object representation in monkeys and humans. *Journal of Cognitive Neuroscience*, 14: 2, 187–198 [10.1162/089892902317236830].

Skidmore AK (1989): A comparison of techniques for calculating gradient and aspect from a gridded digital elevation model. *International Journal of Geographical Information Science*, 3: 4, 323–334.

Skidmore AK (2007): Evolution of methods for estimating slope gradient and aspect from digital elevation models. In: Fisher P (ed.) *Classics from IJGIS: Twenty Years of the International Journal of Geographical Information Science and Systems*, CRC Press, Boca Raton, USA, 111–117.

Sklar LS and Dietrich WE (2001): Sediment and rock strength controls on river incision into bedrock. *Geology*, 29: 12, 1087–1090 [10.1130/0091-7613(2001)029<1087:SARSCO>2.0.CO;2].

Smemoe CM, Nelson EJ, Zundel AK and Miller AW (2007): Demonstrating floodplain uncertainty using flood probability maps. *Journal of the American Water Resources Association*, 43: 2, 359–371 [10.1111/j.1752-1688.2007.0002 8.x].

Smith B (1995): On drawing lines on a map. In: Frank AU, Kuhn W and Mark DM (eds.) *Lecture Notes in Computer Science*, 988. Spatial Information Theory. A Theoretical Basis for GIS. Proceedings of COSIT'95, 21–23 September 1995, Semmering, Austria, 475–484.

Smith B (2001): Fiat objects. *Topoi*, 20: 2, 131–148 [10.1023/A:1017948522031].

Smith B and Mark DM (1998): Ontology and geographic kinds. In: Poiker TK and Chrisman N (eds.) *Proceedings of the 8th International Symposium on Spatial Data Handling (SDH98)*, Vancouver, Canada, 12–15 July 1998, 308-320.

Smith B and Mark DM (2001): Geographical categories: An ontological investigation. *International Journal of Geographical Information Science,* 15: 7, 591–612 [DOI: 10.1080/13658810110061199].

Smith B and Mark DM (2003): Do mountains exist? Towards an ontology of landforms. *Environment and Planning B: Planning and Design*, 30: 3, 411–427.

Smith B and Varzi AC (1997): Fiat and bona fide boundaries: Towards an ontology of spatially extended objects. *Lecture Notes in Computer Science*, 1329, Spatial Information Theory. A Theoretical Basis for GIS. Proceedings of COSIT'97, 15–18 October 1997, Laurel Highlands, USA, 103–119 [10.1007/3-540-63623-4_45].

Smith B and Varzi AC (2000): Fiat and Bona Fide Boundaries. *Philosophy and Phenomenological Research*, 60: 2, 401–420.

Snodgrass JG and Vanderwart M (1980): A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity and visual complexity. *Journal of Experimental Psychology*, 6: 2, 174–215.

Sørensen R and Seibert J (2007): Effects of DEM resolution on the calculation of topographical indices: TWI and its components. *Journal of Hydrology,* 347: 1–2, 79–89 [10.1016/j.jhydrol.2007.09.001].

Sparks BW (1986): Geomorphology. Longman Group, Essex, UK.

Speight JG (1968): Parametric description of landform. In: Stewart GA (ed.) *Land Evaluation*. Proceedings of the CSIRO/UNESCO Symposium, Canberra, Australia, 239–250.

Speight JG (1977): Landform pattern description from aerial photographs. *Photogrammetria*, 32: 5, 161–182.

Speight JG (1990): Landform. In: McDonald RC, Isbell RF, Speight JG, Walker J and Hopkins MS (eds.) *Australian Soil and Land Survey Field Handbook*, Inkata Press, Melbourne, Australia, 9–57.

Straumann RK (2009): Experiences in developing landform ontologies. In: Purves RS, Gruber S, Hengl T and Straumann, RK (eds.) *Proceedings of Geomorphometry 2009*, 31 August – 2 September 2009, Zurich, Switzerland, 17–21.

Straumann RK and Korup O (2009): Quantifying postglacial sediment storage at the mountain-belt scale. *Geology*, 37: 12, 1079–1082 [10.1130/G30113A.1].

Straumann RK and Purves RS (2007): Resolution sensitivity of a compound terrain derivative as computed from LiDAR-based elevation data. In: Fabrikant SI and Wachowicz M (eds.), *Lecture Notes in Geoinformation and Cartography*, The European Information Society. Leading the Way with Geo-Information. Proceedings of 10th AGILE International Conference on Geographic Information Science, 8–11 May 2007, Aalborg, Denmark, 87–109 [10.1007/978-3-540-72 385-1_5].

Straumann RK and Purves RS (2008): Delineation of valleys and valley floors. In: Cova TJ, Miller HJ, Beard K, Frank AU and Goodchild MF (eds.) *Lecture Notes in Computer Science*, 5266, Proceedings of the 5th International Conference on Geographic Information Science (GIScience 2008), 23–26 September 2008, Park City, USA, 320–336 [10.1007/978-3-540-87473-7_21].

Sulebak JR and Hjelle Ø (2003): Multiresolution Spline Models and Their Applications in Geomorphology. In: Evans IS, Dikau R, Tokunaga E, Ohmori H and Hirano M (eds.) *Concepts and Modelling in Geomorphology: International Perspectives*, Terrapub, Tokyo, Japan, 221–237.

Summerfield MA (1991): Global geomorphology. An introduction to the study of landforms. Longman, Harlow, UK.

SUMO (2009): Suggested Upper Merged Ontology, http://www.ontologyportal.org.

Swanson FJ, Kratz TK, Caine N and Woodmansee RG (1988): Landform effects on ecosystem patterns and processes. *BioScience*, 38: 2, 92–98 [10.2307/1310614].

T

Tate NJ and Wood J (2001): Fractals and scale dependencies in topography. In: Tate NJ and Atkinson PM (eds.) Modelling Scale in Geographical Information Science. John Wiley & Sons, Chichester, UK, 35–51.

The Nature Conservancy (2004): The Nature Conservancy in New Hampshire. Granite State Glances. New Conservation Tool for the Ashuelot River Watershed http://www.nature.org/wherewework/northamerica/states/newhampshire/news/news1550.html.

Thomasson AL (2001): Geographic objects and the science of geography. *Topoi*, 20: 2, 149–159 [10.1023/A:1017900607919].

Thompson JA, Bell JC and Butler CA (2001): Digital elevation model resolution: effects on terrain attribute calculation and quantitative soil-landscape modeling. *Geoderma*, 100: 1–2, 67–89 [10.1016/S0016-7061(00)00081-1].

Tomlin CD (1990): Geographic Information Systems and Cartographic Modelling. Prentice Hall, Englewood Cliffs, USA.

Travis MR, Elsner GH, Iverson WD and Johnson CG (1975): VIEWIT: Computation of seen areas, slope, and aspect for land-use planning. General Technical Report PSW-GTR-11. Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture. Berkeley, USA.

Tribe A (1990): Towards the automated recognition of landforms (valley heads) from digital elevation models. In: Brassel K and Kishimoto H (eds.) *Proceedings of the 4th International Symposium on Spatial Data Handling, Volume 1*, Zurich, Switzerland, 23–27 July 1990, 45–52.

Tribe A (1991): Automated recognition of valley heads from digital elevation models. *Earth Surface Processes and Landforms*, 16: 1, 33–49 [10.1002/esp.3290160105].

Tribe A (1992): Problems in automated recognition of valley features from digital elevation models and a new method toward their resolution. *Earth Surface Processes and Landforms*, 17: 5, 437–454 [10.1002/esp.3290170504].

TRIPOD (2009): Project Tripod, http://tripod.shef.ac.uk.

Trochim WM (2006): The Research Methods Knowledge Base: Likert Scaling. Web Center of Social Research Methods. http://www.socialresearchmethods.net/kb/scallik.php.

Troeh FR (1965): Landform equations fitted to contour maps. *American Journal of Science*, 263, 616–627.

U

Unwin D (1981): Introductory Spatial Analysis. Methuen & Co., London, UK.

U.S. Geological Survey (2005): SDTS. View the Standard, http://mcmcweb.er.usgs.gov/sdts/standard.html.

U.S. Department of Agriculture (2005) Natural Resources Conservation Service (NRCS) National Soil Survey Handbook (NSSH), Part 629, Glossary of landform and geologic terms, http://soils.usda.gov/technical/handbook/contents/part629.html.

V

van Asselen S and Seijmonsbergen AC (2006): Expert-driven semi-automated geomorphological mapping for a mountainous area using a laser DTM. *Geomorphology*, 78: 3–4, 309–320 [10.1016/j.geomorph.2006.01.037].

Vance D, Bickle M, Ivy-Ochs S and Kubik PW (2003): Erosion and exhumation in the Himalaya from cosmogenic isotope inventories of river sediments. *Earth and Planetary Science Letters*, 206: 3–4, 273–288 [10.1016/S0012-821X(02)01102-0].

Verkehrsverband Region Gürbetal (s.a.): http://www.guerbetal.ch.

Vieux BE (1993): DEM aggregation and smoothing effects on surface runoff modeling. *Journal of Computing in Civil Engineering*, 7: 3, 310–338 [10.1061/(ASCE)0887-3801(1993)7:3(310)].

Vittinghoff E, Glidden DV, Shiboski SC and McCulloch CE (2005): Regression Methods in Biostatistics. Linear, Logistic, Survival, and Repeated Measures Models. Springer Verlag, New York, USA.

Voegelin CF and Voegelin FM (1957): Hopi domains: A lexical approach to the problem of selection. Memoir 14, International Journal of American Linguistics, Indiana University Publications in Anthropology and Linguistics.

W

Walsh SJ, Butler DR and Malanson GP (1998): An overview of scale, pattern, process relationships in geomorphology: A remote sensing and GIS perspective. *Geomorphology*, 21: 3–4, 183–205 [10.1016/S0169-555X(97)00057-3].

Wang ZY, Li Y and He Y (2007): Sediment budget of the Yangtze River. *Water Resources Research*, 43, W04401 [10.1029/2006WR005012].

Weibel R and Heller M (1991): Digital Terrain Modelling. In: Maguire DJ, Goodchild MF and Rhind DW (eds.) Geographical Information Systems: Principles and Applications. Longman, London, UK, 269–297.

Whittow JB (2000): The Penguin Dictionary of Physical Geography. Penguin Books, London, UK.

Wikipedia (s.a.): http://wikipedia.org, English: http://en.wikipedia.org, German: http://de.wikipedia.org,

Wikipedia DE (2008): "Gürbetal" http://de.wikipedia.org/wiki/G%C3%Bcrbetal (accessed 12 June 2008)

Wikipedia DE (2009): "Engstligenalp" http://de.wikipedia.org/wiki/Engstligenalp (accessed 6 November 2009)

Wilkinson GG (2005): Results and implications of a study of fifteen years of satellite image classification experiments. *IEEE Transactions on Geoscience and Remote Sensing*, 43: 3, 433–440 [10.1109/TGRS.2004.837325].

Williams WA, Jensen ME, Winne JC and Redmond RL (2000): An automated technique for delineating and characterizing valley-bottom settings. *Environmental Monitoring and Assessment*, 64: 1, 105–114 [10.1023/A:1006471427421].

Wilson JP and Gallant JC (2000): Digital Terrain Analysis. In: Wilson JP and Gallant JC (eds.) Terrain Analysis. John Wiley & Sons, New York, USA, 1–27.

Wilson JP, Repetto PL and Snyder RD (2000): Effect of data source, grid resolution, and flow-routing method on computed topographic attributes. In: Wilson JP and Gallant JC (eds.) Terrain Analysis. Principles and Applications. John Wiley & Sons, New York, USA, 133–161.

Wolock DM and Price CV (1994): Effects of digital elevation model map scale and data resolution on a topography-based watershed model. *Water Resources Research*, 30: 11, 3041–3052.

Wood JD (1996): The Geomorphological Characterisation of Digital Elevation Models. PhD thesis, University of Leicester, UK, http://www.soi.city.ac.uk/~jwo/phd.

Wood JD (1998): Modelling the continuity of surface form using digital elevation models. In: Poiker T and Chrisman N (eds.) *Proceedings of the 8th International Symposium on Spatial Data Handling*, Vancouver, Canada, 11–15 July 1998, 725–736.

Wood JD, Fisher PF, Dykes JA, Unwin DJ and Stynes K (1999): The use of the landscape metaphor in understanding population data. *Environment and Planning B: Planning and Design*, 26: 2, 281–295 [10.1068/b260281].

Worboys MF (2001): Nearness relations in environmental space. *International Journal of Geographical Information Science*, 15: 7, 633–651 [10.1080/13658810110061162].

WordNet (2009): WordNet 2.1, http://wordnet.princeton.edu.

X

Xu R and Wunsch II D (2005): Survey of clustering algorithms. *IEEE Transactions on Neural Networks*, 16: 3, 645–678 [10.1109/TNN.2005.845141].

Y

Young M (1978): Terrain analysis: Program documentation. Report 5 on Grant DA-ERO-591-73-G0040, Statistical characterization of altitude matrices by computer. Department of Geography, University of Durham, UK.

Z

Zadeh LA (1965): Fuzzy Sets. *Information and Control*, 8, 338–353.

Zebker HA and Goldstein RM (1986): Topographic mapping from interferometric synthetic aperture radar observations. *Journal of Geophysical Research*, 91: B5, 4993–4999 [10.1029/JB091iB05p04993].

Zevenbergen LW and Thorne CR (1987): Quantative analysis of land surface topography. *Earth Surface Processes and Landforms*, 12: 1, 47–56 [10.1002/esp.3290120107]

Zhang W and Montgomery DR (1994): Digital elevation model grid size, landscape, representation, and hydrologic simulations. *Water Resources Research*, 30: 4, 1019–1028.

Zhang X, Drake NA, Wainwright J and Mulligan M (1999): Comparison of slope estimates from low resolution DEMs: Scaling issues and a fractal method for their solution. *Earth Surface Processes and Landforms*, 24: 9, 763–779. [10.1002/(SICI)1096-9837(199908)24:9<763::AID-ESP9>3.0.CO;2-J]

Zhou Q and Liu X (2004): Analysis of errors of derived slope and aspect related to DEM data properties. *Computers & Geosciences*, 30, 369–378 [10.1016/j.cageo.2003.07.005].

Zhou Q, Lees B and Tang G (eds., 2008): Advances in Digital Terrain Analysis. Springer, Berlin, Germany [10.1007/978-3-540-77800-4].

Appendix A: Primary and secondary terrain parameters

Besides the distinction into primary terrain parameters (which are “computed directly from the DEM”) and secondary terrain parameters (that “involve combinations of two or more primary attributes” (Gallant and Wilson 1996: 713), there is a more general classification of raster operations. That classification goes back to Tomlin (1990) and can be applied to terrain parameters in addition to the above distinction. The following classes of raster operation are distinguished regarding their spatial footprint (Longley et al. 2001: 282):

Local operations	The analysis is done in cell-by-cell manner.
Focal operations	The analysis is done on the central cell and an immediate, confined neighbourhood.
Zonal operations	An aggregate measure is computed for (usually contiguous) blocks of cells.
Global operations	The analysis gives a result for the entire raster and/or considers potentially all cells present.

Table 1 gives an overview of the most prominent primary terrain parameters in the sense of Wilson and Gallant (2000) along with a classification of the underlying raster operations according to the afore-mentioned scheme by Tomlin (1990).

Instead of the term “curvature” the term “convexity” is also used sometimes. This is a reminder, that – as a convention – convexity is usually denoted by positive curvature (Evans 1980: 278).

Mean curvature is sometimes regarded as secondary terrain parameter, since it can be computed from any two mutually perpendicular curvatures. The classification into primary or secondary nature of this terrain parameter is not clear, since, as Shary et al. (2002: 13, referring to Gauss (1827)) show, mean curvature can also be computed directly from DEM partial derivatives. The same applies for other curvatures, too. Shary (1995) presented a “complete system of curvatures”. There he also makes a point to regard the three independent curvatures mean curvature, unsphericity and difference curvature as primary and all other curvatures as secondary, since they can be computed from the former.

Note, that while the calculation of certain terrain parameters involve multiple calculation steps (upslope area, drainage network, catchment in Table 1), they are still regarded primary terrain parameters. This is due to the fact, that while e.g. upslope area usually involves the computation of flow directions and afterwards the summation of individual cells (flow accumulation), it still does not include the “combination of two or more primary attributes” as the definition of secondary parameters would require.

Table 1: Primary terrain parameters.

Parameter	Reference(s)	Description	Footprint	(S)ynonyms, (R)elated terms
Altitude	Wilson and Gallant (2000)	Elevation	local	
Elevation percentile	Wilson and Gallant (2000)	Proportion of cells lower than the cell under consideration	focal or zonal	
Surface area	Li et al. (2005)	True surface area (unequal to planimetric area)	focal	
Slope gradient	Evans (1972), Wilson and Gallant (2000)	Magnitude of the slope vector	focal	S/R: slope
Slope aspect	Evans (1972), Wilson and Gallant (2000)	Azimuth of the slope vector	focal	S: exposition
Profile curvature	Evans (1972), Wood (1996), Wilson and Gallant (2000)	Rate of change of slope gradient; curvature of the line formed by intersection of the surface with the normal section perpendicular to the contour line (Shary et al. 2002) (or parallel to flow line)	focal	S: vertical curvature (Shary et al. 2002)
Plan curvature	Evans (1972), Wood (1996), Wilson and Gallant (2000)	Rate of change of slope aspect along a contour line	focal	S: contour curvature (Schmidt et al. 2003)
Tangential curvature	Krcho (1973, 1991) as cited in Mitasova and Hofierka (1993), Wilson and Gallant (2000)	Plan curvature multiplied by slope gradient (Wilson and Gallant 2000); curvature of the line formed by intersection of the surface with plane normal to flow line (Gallant and Wilson 1996); curvature of the line formed by intersection of the surface with the normal section tangential to the contour line (Shary et al. 2002)	focal	S: horizontal curvature (Shary et al. 2002)
Mean curvature	Li et al. (2005)	Average of curvatures of any two mutually perpendicular normal sections; small values for close to minimal surfaces (Shary et al. 2002)	focal	
Minimum curvature	Wood (1996), Shary et al. (2002)	Curvature of the line formed by intersection of the surface with that normal section yielding the minimum curvature	focal	
Maximum curvature	Wood (1996), Shary et al. (2002)	Curvature of the line formed by intersection of the surface with that normal section yielding the maximum curvature	focal	

Table 1 (continued).

Parameter	Reference(s)	Description	Footprint	(S)ynonyms, (R)elated terms
Flow direction	Li et al. (2005)	Direction(s) of flow from a cell into neighbouring cells	focal	R: local drain direction (Burrough and McDonnell 1998)
Upslope area	Wilson and Gallant (2000)	Catchment area above a short length of contour line	focal (flow direction), zonal (flow accumulation)	S: upslope contributing area (Gallant and Wilson 1996), flow accumulation (Li et al. 2005) R: upness index (Dowling et al. 2003)
Dispersal area	Wilson and Gallant (2000)	Area downslope from a short length of contour line	focal (flow direction), zonal (flow accumulation)	
Specific catchment area	Wilson and Gallant (2000)	Upslope area per unit width of contour line		S: upslope area per unit contour length (Wolock and Price 1994)
Drainage network	Li et al. (2005)	Usually obtained through thresholding of flow accumulation	focal (flow direction), zonal (flow accumulation), local (thresholding)	S: stream channel (Burrough and McDonnell 1998), blueline
Catchment	Li et al. (2005)	Membership of a point to a catchment	focal (flow direction), zonal (flow accumulation), local (thresholding), zonal (catchment)	
Flow path length	Wilson and Gallant (2000)	Maximum distance of water flow to a point	zonal	

Table 1 (continued).

Parameter	Reference(s)	Description	Footprint	(S)ynonyms, (R)elated terms
Upslope length	Wilson and Gallant (2000)	Mean length of flow paths to a point	zonal	
Dispersal length	Wilson and Gallant (2000)	Distance from a point in a catchment to the outlet		
Catchment length	Wilson and Gallant (2000)	Distance from the highest point of the catchment to the outlet		
Roughness	Mark (1975), Felicísimo (1994), Li et al. (2005)	Measures for the roughness of an area	focal	
Relief	Evans (1972)	Standard deviation, interquartile range or range of elevation in an area	focal or zonal	
Viewshed	Li et al. (2005)	Area viewable from a point or a set of points	global	

Wilson and Gallant (2000) present various measures (elevation, gradient) that are aggregated over either upslope areas, dispersal areas or catchments. These are not detailed here.

Examples of secondary terrain parameters, i.e. parameters computed from a combination of two or more terrain parameters, encompass the following:

Stream power index:

$$\mathrm{SPI} = A_s \cdot \tan(\beta) \tag{1}$$

Sediment transport (capacity) index (Moore and Burch 1986):

$$\mathrm{LS} = (m+1)\left(\frac{A_s}{22.13}\right)^m \left(\frac{\sin(\beta)}{0.0896}\right)^n \tag{2}$$

where *m* (constant) = 0.4 to 0.6, and *n* (constant) = 1.2 to 1.3 (Moore and Wilson 1992).

Topographic (wetness) or *compound topographic index* (TWI or CTI) (Beven and Kirkby 1979, Quinn et al. 1995):

$$\mathrm{TWI} = \ln\left(\frac{A_s}{\tan(\beta)}\right) \tag{3}$$

where: A_s: Specific catchment area, and β: slope gradient

Various *radiation indices*: Wilson and Gallant (2000) list several indices and discuss their computation in the software package SRAD. Dubayah and Rich (1995) review physically-based radiation formulas and discuss the GIS solar radiation models ATM and SOLARFLUX (see also Burrough and McDonnell (1998) for further references).

Appendix B: Evans-Young method of slope computation

One of the several algorithms to estimate various partial derivatives of surfaces is termed the *Evans-Young method*. This shall be shown in detail here, while other algorithms are summarised in Table 1 in Section 2.2.1 of this thesis. The calculus for the Evans-Young method has been proposed by Young (1978) together with Evans (1979) and later described in Pennock et al. (1987) (Shary et al. 2002: 11). Fig. 1 shows the coding of the nine cells in a 3x3 neighbourhood in a raster DEM.

z_1	z_2	z_3
z_4	z_5	z_6
z_7	z_8	z_9

Fig. 1: Coding of raster cells.

In the Evans-Young method a second-order polynomial of the form

$$f = ax + by + \frac{cx^2}{2} + \frac{dy^2}{2} + exy + z_0 \tag{1}$$

is fitted by the least-squares method to any 3 by 3 neighbourhood in a DEM. This six term polynomial will not pass through the nine data points exactly, but smooth the elevation information a bit. This has been claimed by Evans (1980) and Evans and Cox (1999) to be an antidote against data errors and possibly rounding (Guth 1995).

In equation (1) a through e denote different partial derivatives of the polynomial at the central point of the neighbourhood where $x = y = 0$ (equations 2 to 6); for a full account of the derivation of this method see the appendix in Pennock et al. (1987)):

$$a = f_x = \frac{\partial z}{\partial x} \tag{2}$$

$$b = f_y = \frac{\partial z}{\partial y} \tag{3}$$

$$c = f_{xx} = \frac{\partial^2 z}{\partial x^2} \tag{4}$$

$$d = f_{yy} = \frac{\partial^2 z}{\partial y^2} \tag{5}$$

$$e = f_{xy} = \frac{\partial^2 z}{\partial x \partial y} \tag{6}$$

Using the coding shown in Fig. 1 the different derivatives can be estimated using the equations (7) to (11) were *s* denotes grid resolution (formulas not according to Pennock et al. (1987) but to the more elegant version by Shary et al. (2002); except for (11), where the latter version is incorrect (personal communication with Peter Shary, March 2007):

$$f_x = a = \frac{z_3 + z_6 + z_9 - z_1 - z_4 - z_7}{6s} \tag{7}$$

$$f_y = b = \frac{z_1 + z_2 + z_3 - z_7 - z_8 - z_9}{6s} \tag{8}$$

$$f_{xx} = c = \frac{z_1 + z_4 + z_7 + z_3 + z_6 + z_9 - 2(z_2 + z_5 + z_8)}{3s^2} \tag{9}$$

$$f_{yy} = d = \frac{z_1 + z_2 + z_3 + z_7 + z_8 + z_9 - 2(z_4 + z_5 + z_6)}{3s^2} \tag{10}$$

$$f_{xy} = e = \frac{z_3 + z_7 - z_1 - z_9}{4s^2} \tag{11}$$

From the first partial derivatives in *x* and *y* direction, f_x and f_y, gradient and aspect can be computed using the following formulas:

$$\text{Gradient } [°] = \arctan\left(\sqrt{{f_x}^2 + {f_y}^2}\right) \tag{12}$$

$$\text{Aspect } [°] = \arctan(f_y / f_x) \tag{13}$$

For the derivation of second-order derivatives which are extremely sensitive to noise in the data, a smoothing operation has been suggested (cf. Hengl et al. 2003: 19). An alternative smoothing was put forward by Shary et al. (2002) and together with the subsequently applied Evans-Young method termed the *modified Evans-Young method*. According to the authors the filtering by Shary et al. (2002) removes emphasis on grid directions for second-order derivatives of the original Evans-Young method.

Appendix C: Listing of landform (element) terms

The following pages contain listings of terms related to landform and landform elements. The terms have been gathered from the sources detailed in Section 3.2 of this thesis under exclusion of the terms listed in Section 3.2.8. As explained in Section 3.3 the landform-related terms have been grouped into three superordinate categories *topographic eminences*, *topographic depressions* and *topographic plains*. In this listing these three category sets are followed by a listing of terms related to *landform elements*. Lastly, there is a brief listing, whose members could not be mapped onto any of the superordinate categories.

Relations

Depending upon source reference work (see Section 3.2) the listing of terms contains different relations between individual categories (Table 1).

Table 1: Abbreviations used within different reference works.

Source	**Abbreviation**	**Description**
WNET	HR	Hypernym (A whole class of specific instances. Y is a hypernym of X if X is a (kind of) Y.)
	HO	Hyponym (A member of a class. X is a hyponym of Y if X is a (kind of) Y.) Hyponyms are listed recursively; e.g: A is a kind of B which is a kind of C which is a kind of D is indicated in the entry regarding A as: HR: B → C → D.
	HO*	Hyponym (without hyponyms of its own)
	HN	Holonym (The whole of which the meronym names a part. Y is a holonym of X if X is a part of Y.)
	MN	Meronym (The name of a constituent part of, the substance of, or a member of something. X is a meronym of Y if X is a part of Y.)
SDTS	IT	Included type
		* in more than one of the listed categories;
		° in more than one category, listed and unlisted ones
OSHO	KO	Is kind of
	SK	Has sub-kind(s)
AFTT	UF	Used for
	R	Related term (non-hierarchical relationship)
	NT	Narrower term
	BT	Broader term
SUMO-G	SC	Superclass

Topographic eminences

Category	Definition, context	Source
(Natural) elevation	a raised or elevated geological formation HR: (geological) formation → (physical) object HO: highland, upland; hill; mountain, mount; promontory, headland, head, foreland; ridge; swell HN: – MN: slope, incline, side (an elevated geological formation)	WNET
UplandArea	An UplandArea is a LandArea elevated above the surrounding terrain SC: LandForm	SUMO-G
Highland, upland	elevated (e.g., mountainous) land HR: (natural) elevation → (geological) formation → (physical) object HO: down; tableland, plateau HN: – MN: (inherited) slope, incline, side	WNET
Mountain, mount	a land mass that projects well above its surroundings; higher than a hill HR: (natural) elevation → (geological) formation → (physical) object HO: alp; ben; seamount; volcano HN: – MN: mountain peak (the summit of a mountain); mountainside, versant (the side or slope of a mountain)	WNET
Mount	a mountain or hill IT: bald°, bank°, bery°, cerrito, cerro*, cinder cone, cuesta*, dome, drumlin*, foothill, hill, hillock, hummock°, kame*, knob, knoll, lava cone, monadnock, mound, mountain, pingo, rise, sand dune*, sand hills*, seaknoll, seamount, shield volcano, volcano	SDTS
Mountain	a large natural elevation of the earth's surface rising abruptly from the surrounding level.	OSHO
Mountain	a mountain is a high, rocky LandForm, usually with steep sides and a pointed or rounded top, and higher than a Hill SC: LandForm, UplandArea	SUMO-G
Mountains	landmasses that project conspicuously above their surroundings UF: cerros, cordilleras, foothills, hills, knolls, mounds, mounts R: anticlines, massifs, mesas, seamounts, volcanoes NT: continental divides, mountain ranges, mountain summits, ridges BT: physiographic features	AFTT
Hill	a local and well-defined elevation of the land HR: (natural) elevation → (geological) formation → (physical) object HO: butte; foothill; knoll, mound, hummock, hammock; tor HN: – MN: hillside (the side or slope of a hill)	WNET
Hill	a naturally raised area of land, not as high as a mountain	OSHO
Hill	a Hill is a raised part of the earth's surface with sloping sides – an old mountain which because of erosion has become shorter and more rounded SC: LandForm, UplandArea	SUMO-G
Hill	a small, isolated elevation, smaller than a mountain	DIGEST
Alp	any high mountain HR: mountain, mount → (natural) elevation → (geological) formation → (physical) object HO, HN: – MN: (inherited) mountain peak; mountainside, versant	WNET
Ben	a mountain or tall hill HR: mountain, mount → (natural) elevation → (geological) formation → (physical) object HO, HN: – MN: (inherited) mountain peak; mountainside, versant	WNET
Foothill	a relatively low hill on the lower slope of a mountain HR: hill → (natural) elevation → (geological) formation → (physical) object HO, HN: – MN: (inherited) hillside	WNET
Range, mountain range, range of mountains, chain, moun- tain chain, chain of mountains	a series of hills or mountains HR: (geological) formation → (physical) object HO, HN: – MN: (part) massif (a block of the earth's crust bounded by faults and shifted to form peaks of a mountain range), pass, mountain pass, notch (the location in a range of mountains of a geological formation that is lower than the surrounding peaks)	WNET
Mount_range	a series of connected and aligned mountains or mountain ridges IT: mountain range, range*°, seamount chain, seamount group, seamount range	SDTS
Mountain ranges	(a) chains of hills or mountains; (b) somewhat linear, complex mountainous or hilly areas UF: ranges (physiographic), sierra R, NT: – BT: mountains	AFTT
MountainRange	a MountainRange is a row or chain of connected mountains SC: UplandArea	SUMO-G
Massif	a block of the earth's crust bounded by faults and shifted to form peaks of a mountain range HR: (geological) formation → (physical) object HO: – HN: range, mountain range, range of mountains, chain, mountain chain, chain of mountains (a series of hills or mountains) MN: –	WNET
Massifs	massive topographic and structural features, commonly formed of rocks more rigid than those of their surroundings UF, NT: – R: mountains, plateaus BT: physiographic features	AFTT

Category	Definition, context	Source
Volcano	a mountain formed by volcanic material HR: mountain, mount → (natural) elevation → (geological) formation → (physical) object HO, HN: – MN: volcanic crater, crater; (inherited) mountain peak; mountainside, versant	WNET
Volcano	a mountain or hill, often conical, formed around a vent in the earth's crust through which molten rock, ash, or gases are or have been expelled	DIGEST
Volcano	a Volcano in the broadest sense, i.e., a region containing a vent through which magmous and/or pyroclastic materials are passed from the interior of the Earth to its surface (atmospheric or underwater) SC: LandForm	SUMO-G
Volcanoes	vents in the surface of the Earth through which magma and associated gases erupt; also, the forms or structures, usually conical, that are produced by the erupted material UF: – R: craters, mountains NT: – BT: volcanic features	AFTT
VolcanicMountain	a VolcanicMountain is a cone-shaped mountain formed out of rock or ash thrown up from inside the earth, frequently with an opening or depression at the top SC: Mountain, Volcano	SUMO-G
VolcanicCone	a VolcanicCone is a hill of lava or pyroclastics surrounding a volcanic vent. Not as high as a VolcanicMountain. SC: Hill, Volcano	SUMO-G
Volcanic dike	a steep ridge of igneous rock	DIGEST
Knoll, mound, hillock, hummock, hammock	a small natural hill HR: hill → (natural) elevation → (geological) formation → (physical) object HO: anthill, formicary; kopje, koppie; molehill HN: – MN: (inherited) hillside	WNET
Hummock	an area of higher elevation within a swamp, bog, or marsh	DIGEST
Kopje, koppie	a small hill rising up from the African veld HR: knoll, mound, hummock, hammock → hill → (natural) elevation → (geological) formation → (physical) object HO, HN, MN: –	WNET
Tor	a high rocky hill HR: hill → (natural) elevation → (geological) formation → (physical) object HO, HN: – MN: (inherited) hillside	WNET
Pingo	a cone or dome shaped mound or hill of peat or soil, usually with a core of ice. It is found in tundra regions and is produced by the pressure of water or ice accumulating underground and pushing upward.	DIGEST
Diapir	a domed rock formation where a core of rock has moved upward and pierced through the more brittle overlying strata HR: (geological) formation → (physical) object HO, HN, MN: –	WNET
Tableland, plateau	a relatively flat highland HR: highland, upland → (natural) elevation → (geological) formation → (physical) object HO: mesa, table; terrace, bench HN: – MN: (inherited) slope, incline, side	WNET
Plateau	an elevated and comparatively level expanse of land IT: butte, guyot, intermontane plateau, mesa, tableknoll, tableland, tablemount	SDTS
Plateaus	comparatively flat areas of great extent and elevation; specif. extensive land regions considerably above the adjacent country or above sea level; commonly limited on at least one side by an abrupt descent, have flat or nearly smooth surfaces but are often dissected by deep valleys and surmounted by high hills or mountains, and have a large part of their total surface at or near the summit level UF: table mountains, tablelands R: flats, massifs, mesas, plains NT: – BT: physiographic features	AFTT
Plateau	a Plateau is a flat upland area with one steep face, elevated plain SC: LandForm, UplandArea	SUMO-G
Mesa, table	flat tableland with steep edges HR: tableland, plateau → highland, upland → (natural) elevation → (geological) formation → (physical) object HO, HN, MN: –	WNET
Mesas	very broad, flat-topped, usually isolated hills or mountains of moderate height bounded on at least one side by a steep cliff or slope and representing an erosion remnant UF: buttes R: flats, mountains, plains, plateaus NT: – BT: physiographic features	AFTT
Mesa	a Mesa is a land formation having a relatively flat top and steep rock walls SC: LandForm, UplandArea	SUMO-G
Butte	a hill that rises abruptly from the surrounding region; has a flat top and sloping sides HR: hill → (natural) elevation → (geological) formation → (physical) object HO, HN: – MN: (inherited) hillside	WNET
Butte	a Butte is an Upland raised sharply from the surrounding region. Smaller in area than a Mesa. SC: LandForm, UplandArea	SUMO-G

Category	Definition, context	Source
Ridge, ridgeline	a long narrow range of hills HR: (geological) formation → (physical) object HO: arete (a sharp narrow ridge found in rugged mountains), hogback, horseback (a narrow ridge of hills) HN, MN: –	WNET
Ridge	a long narrow natural elevation or striation HR: (natural) elevation → (geological) formation → (physical) object HO: bank; bar; dune, sand dune; esker; ledge, shelf; reef; ripple mark HN: – MN: (inherited) slope, incline, side	WNET
Ridge	a long narrow natural elevation on the floor of the ocean HR: (geological) formation → (physical) object HO: Mid-Atlantic Ridge (a very long narrow elevation on the ocean floor that runs all the way from Iceland in the North Atlantic to Bouvet Island in the South Atlantic) HN, MN: –	WNET
Ridge	a long and narrow upland with steep sides IT: arete, beach cusps, beach ridge, cerro*, crest, cuesta*, drumlin*, esker, kame*, range*°, sand dune*, sand hills*, sill*, spur°, volcanic dike	SDTS
Ridges	elevations with a narrow elongated crest which can be part of a hill or mountain UF: aretes, beach ridges, cuestas, eskers, hogbacks, icecap ridges, rises (seafloor), spurs (physiographic) R: cliffs, mountain summits, seafloor features NT: drumlins BT: mountains	AFTT
Drumlin	a mound of glacial drift HR: drift → substance, matter HO, HN, MN: -	WNET
Drumlins	low, smoothly rounded, elongate oval hills, mounds or ridges of compact glacial till built under the margin of the ice and shaped by its flow, or carved out of an older moraine by readvancing ice UF: – R: glacier features NT: – BT: ridges	AFTT
Esker	a long winding ridge of post glacial gravel and other sediment; deposited by meltwater from glaciers or ice sheets HR: ridge → (natural) elevation → (geological) formation → (physical) object HO, HN, MN: –	WNET
Esker	a long, narrow ridge of sand and gravel deposited by a glacial stream	DIGEST
Moraine	An accumulation of soil and stone debris deposited by a glacier	DIGEST
Moraine	an accumulation of boulders, stones, or other debris carried and deposited by a glacier IT: delta moraine, end moraine, glacial moraine, lateral moraine, terminal moraine	SDTS
Moraines	accumulations of earth and stones carried and deposited by a glacier UF: – R: glacier features NT: – BT: physiographic features	AFTT
Sand dune/sand hills	ridges or hills of sand	DIGEST
Dunes	low mounds, ridges, banks, or hills of loose, wind-blown granular material, either bare or covered with vegetation, capable of movement from place to place but always retaining their characteristic shape UF: interdune troughs, sandy areas R: beaches, deserts NT: – BT: physiographic features	AFTT
Dune, sand dune	a ridge of sand created by the wind; found in deserts or near lakes and oceans HR: ridge → (natural) elevation → (geological) formation → (physical) object HO: seif dune HN, MN: –	WNET
Seif dune	a long and tall sand dune with a sharp crest; common in the Sahara HR: dune, sand dune → ridge → (natural) elevation → (geological) formation → (physical) object HO, HN, MN: –	WNET
Ripple mark	One of a series of small ridges produced in sand by water currents or by wind HR: ridge → (natural) elevation → (geological) formation → (physical) object HO, HN, MN: –	WNET
Down	a rolling treeless highland with little soil HR: highland, upland → (natural) elevation → (geological) formation → (physical) object HO, HN: – MN: (inherited) slope, incline, side	WNET
Pinnacle	a tall, slender, spire-shaped rock projecting from a level or more gently sloping surface IT: chapeiro, coral head, crag*, pillar, precipice*, scar*	SDTS
Ice peak/nunatak	a rocky peak projecting above a surrounding ice field that may be perpetually covered with ice	DIGEST

Topographic depressions

Category	Definition, context	Source
(Natural) depression	a sunken or depressed geological formation HR: (geological) formation → (physical) object HO*: basin; bed, bottom (a depression forming the ground under a body of water); crater; hole, hollow; lowland; sinkhole, sink, swallow hole; trench, deep, oceanic abyss (a long steep-sided depression in the ocean floor); trough; valley, vale HN, MN: –	WNET
Depression	a low area surrounded by higher ground	DIGEST
Lowland	HR: (natural) depression → (geological) formation → (physical) object HO: landfill HN, MN: –	WNET
LowlandArea	A LowlandArea is a LandArea lower than the surrounding region, and usually level land SC: LandForm	SUMO-G
Valley, vale	a long depression in the surface of the land that usually contains a river HR: (natural) depression → (geological) formation → (physical) object HO: dale; glen; gully; hollow, holler; nullah; ravine; rift valley HN, MN: –	WNET
Valley	a long, narrow depression in the Earth's surface, usually with a fairly regular downslope IT: canyon, chasm, coulee°, crevice°, dale, defile*, dell, depression*, drowned valley, glacial gorge, glacial trough, glen, goe, gorge, graben, gulch°, gully°, hollow, ravine°, re-entrant, rift valley, seachannel°, strath, trench*, water gap°	SDTS
Valley	a Valley is an area of low-lying land flanked by higher ground. Valleys typically contain a stream or river flowing along the valley floor. SC: LandForm, LowlandArea	SUMO-G
Valleys	low-lying land bordered by higher ground; especially elongate, relatively large gently sloping depressions of the Earth's surface, commonly situated between two mountains or between ranges of hills or mountains, and often containing a stream with an outlet. UF: forks (physiographic feature), glens, hanging valleys, hollows, median valleys, shelf valleys (seafloor) R: arroyos, basins, gaps, seafloor features NT: canyons BT: physiographic features	AFTT
Valley	a low area more or less enclosed by hills	OSHO
Valley bottom line	a line representation of the lowest part of a valley	DIGEST
Rift valley	a valley with steep sides; formed by a rift in the earth's crust HR: valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Dale	an open river valley (in a hilly area) HR: valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Glen	a narrow secluded valley (in the mountains) HR: valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Hollow, holler	a small valley between mountains HR: valley, vale → (natural) depression → (geological) formation → (physical) object HO: dell, dingle HN, MN: –	WNET
Hollow	an empty space SK: basin, channel, pipe	OSHO
Hole	an aperture in or through something SK: sink(hole)	OSHO
Hole, hollow	a depression hollowed out of solid matter HR: (natural) depression → (geological) formation → (physical) object HO: burrow, tunnel; gopher hole; kettle hole, kettle; pit, cavity; pothole, chuckhole; rabbit burrow, rabbit hole; wormhole HN, MN: –	WNET
Dell, dingle	a small wooded hollow HR: hollow, holler → valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Ravine	a deep narrow steep-sided valley (especially one formed by running water) HR: valley, vale → (natural) depression → (geological) formation → (physical) object HO: canyon, canon; gorge HN, MN: –	WNET
Gully	deep ditch cut by running water (especially after a prolonged downpour) HR: valley, vale → (natural) depression → (geological) formation → (physical) object HO: arroyo; draw; wadi HN, MN: –	WNET
Arroyo	a stream or brook HR: gully → valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET

Category	Definition, context	Source
Arroyos	small deep flat-floored channels or gullies of an ephemeral stream or of an intermittent stream, usually with vertical or steeply cut banks UF: coulees, gullies, wadi bends, wadi junctions, wadi mouths, wadis, washes R: canyons, valleys NT: – BT: physiographic features	AFTT
Draw	a gully that is shallower than a ravine HR: gully → valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Wadi	gully or streambed in northern Africa and the Middle East that remains dry except during rainy season HR: gully → valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Nullah	a ravine or gully in southern Asia HR: valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Gorge	a deep ravine (usually with a river running through it) HR: ravine → valley, vale → (natural) depression → (geological) formation → (physical) object HO: gulch, flume HN, MN: –	WNET
US-gully/gorge, UK-gullies	a long, narrow, deep erosion with steep banks	DIGEST
Gulch, flume	a narrow gorge with a stream running through it HR: gorge → ravine → valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Canyon, canon	a ravine formed by a river in an area with little rainfall HR: ravine → valley, vale → (natural) depression → (geological) formation → (physical) object HO, HN: – MN: canyonside	WNET
Canyon	a Canyon is a narrow valley with steep sides, usually created by erosion SC: LandForm	SUMO-G
Canyons	relatively narrow, deep depressions with steep sides, the bottom of which generally has a continuous slope UF: barrancas, chasms, flumes (natural), gorges, gulches, quebradas, ravines R: arroyos, badlands, cliffs, submarine canyons NT: – BT: valleys	AFTT
Basin	a hollow bowl-shaped depression in the ground, completely bounded at its sides and base by land, that can enable the containment of water (A basin is a hollow in the ground surface. A basin has part bed and bank. A basin typically contains water. A basin has footprint. A basin is connected to a channel, a pipe or a basin or nothing. A basin enables containment of water.) KO: hollow	OSHO
Basin	a Basin is an area of land enclosed or partially enclosed by higher land SC: LandForm	SUMO-G
Basin	any bowl-shaped depression in the surface of the land or ocean floor IT: barrier basin, cauldron, depression*, kettle, non tidal basin, sabkha, sink, sinkhole, tidal basin, wave basin°	SDTS
Basins	Bowl-shaped, natural depressions in the surface of the land or ocean floor UF: asphalt lakes, depressions, pans (geologic) R: bays, cirques, craters, drainage basins, lakes, mineral deposit areas, playas, synclines, valleys NT: storage basins BT: physiographic features	AFTT
Basin	a natural depression in the surface of the land often with a lake at the bottom of it HR: (natural) depression → (geological) formation → (physical) object HO: cirque, corrie, cwm; saltpan; tidal basin HN, MN: –	WNET
Storage basins	basins in which drainage water is naturally detained UF: flood control basins, floodways, retention basins R, NT: – BT: basins	AFTT
Drainage basins	regions or areas bounded by drainage divides and occupied by drainage systems; specifically the tract of country that gathers water originating as precipitation and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water UF: catchments, headwaters, watersheds R: basins, floodplains, streams NT: – BT: hydrographic features	AFTT
River basin, basin	the entire geographical area drained by a river and its tributaries HR: geographic(al) area → region → location → (physical) object HO, HN, MN: –	WNET
Catchment	an area drained by a single watercourse; a natural drainage area which may coincide with a river basin, in which the divides direct the water from the rainfall and percolation into a river. However, where underground flow is involved, the catchment may be larger or smaller than that that may be apparent from the surface relief. IT: drainage basin	SDTS
Crater	a circular-shaped depression at the summit of a volcanic cone or on the surface of the land IT: caldera	SDTS

Category	Definition, context	Source
Crater	a bowl-shaped depression formed by the impact of a meteorite or bomb HR: (natural) depression → (geological) formation → (physical) object HO: collector; lunar crater HN, MN: –	WNET
Craters	circular-shaped depressions at the summit of a volcanic cone or on the surface of the land caused by the impact of a meteorite; man-made depressions caused by an explosion UF: calderas R: basins, volcanoes NT: – BT: physiographic features	AFTT
Volcanic crater, crater	a bowl-shaped geological formation at the top of a volcano HR: (geological) formation → (physical) object HO: caldera (a large crater caused by the violent explosion of a volcano that collapses into a depression), maar (a flat-bottomed volcanic crater that was formed by an explosion; often filled with water) HN: (part) volcano (a mountain formed by volcanic material) MN: –	WNET
Collector	a crater that has collected cosmic material hitting the earth HR: crater → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Cirque, corrie, cwm	a steep-walled semicircular basin in a mountain; may contain a lake HR: basin → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Cirques	bowl-like hollows partially surrounded by cliffs or steep slopes at the head of a glaciated valley UF: cwms R: basins NT: – BT: physiographic features	AFTT
Cirque	a deep natural hollow near the crest of a mountain	SDTS
Pit, cavity	a sizeable hole (usually in the ground) HR: hole, hollow → (natural) depression → (geological) formation → (physical) object HO: barbecue pit; borrow pit; divot; fire pit; quicksand; sandpit; sawpit; tar pit HN, MN: –	WNET
Kettle hole, kettle	a hollow (typically filled by a lake) that results from the melting of a mass of ice trapped in glacial deposits HR: hole, hollow → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Sinkhole, sink, swallow hole	a depression in the ground communicating with a subterranean passage (especially in limestone) and formed by solution or by collapse of a cavern roof HR: (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Sink	a place where a surface water course disappears underground. Common in chalk and limestone areas. Hole, shaft or funnel shaped hollow in lime stone. (A sink is a kind of hole in the ground surface. A sink is a hole located where a stream flows into the ground surface. A sink has a footprint. Sink has synonym sinkhole.) KO: hole	OSHO
Swale	a low area (especially a marshy area between ridges) HR: trough → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Quicksand	a pit filled with loose wet sand into which objects are sucked down HR: pit, cavity → hole, hollow → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Tar pit	a natural accumulation of bitumens at the surface of the earth; often acts as a trap for animals whose bones are thus preserved HR: pit, cavity → hole, hollow → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Trough	a narrow depression (as in the earth or between ocean waves or in the ocean bed) HR: (natural) depression → (geological) formation → (physical) object HO: swale HN, MN: –	WNET

Topographic plains

Category	Definition, context	Source
Plain	a region of general uniform slope, comparatively level, and of considerable extent IT: apron°, archipelago apron, coastal plain°, outwash plain*	SDTS
Plains	regions of general uniform slope, comparatively level and of considerable extent UF: interfluves, llanos R: flats, mesas, plateaus NT: – BT: physiographic features	AFTT
Plain	a Plain is a broad, flat or gently rolling area, usually low in elevation SC: LowlandArea	SUMO-G
Flood plain	an area which is subject to periodic flooding	SDTS
Floodplain	the relatively flat part of the valley bordering a river resulting from alluvium deposited by a river in times of flood. (A floodplain is an area of land. A floodplain is adjacent to rivers. A flood-plain is location of a flood. A floodplain has footprint. A floodplain has synonym flood basin.) KO: area of land	OSHO
Floodplains	flat or nearly flat land along a river or stream or in a tidal area that is covered by water during a flood UF: bottomlands R: alluvial fans, drainage basins NT: – BT: hydrographic features	AFTT
CoastalPlain	CoastalPlain is the class of broad plains areas adjacent to a Sea or Ocean. A coastal plain includes a narrower ShoreArea adjacent to a body of water. SC: Plain	SUMO-G
Flats	relatively level areas within regions of greater relief UF: sabkhas R: mesas, plains, plateaus, playas NT: – BT: physiographic features	AFTT
Saltpan	a shallow basin in a desert region; contains salt and gypsum that was depos-ited by an evaporated salt lake HR: basin → (natural) depression → (geological) formation → (physical) object HO, HN, MN: –	WNET
Salt pan	a flat area of natural surface salt deposits	DIGEST
Sebkha	a natural depression in arid or semi-arid regions whose bed is covered with salt encrusted clayey soil	DIGEST
Playas	closed depressions in an arid or semi-arid region that are periodically inundated by surface runoff, or the salt flat within such a closed basin UF: chotts, kavirs R: basins, flats, wetlands NT: – BT: physiographic features	AFTT
Delta	a low triangular area where a river divides before entering a larger body of water HR: (geological) formation → (physical) object HO, HN, MN: –	WNET
Deltas	flat plains formed by alluvial deposits at the mouth of a stream UF: – R: alluvial fans, estuaries NT: – BT: physiographic features	AFTT
Delta	a Delta is a LandForm composed of silt or other alluvium, deposited at or near the mouth of a river or stream as it enters a body of relatively static water. Typically a delta is flat and fan-shaped. SC: LandForm	SUMO-G
Delta	a tract of alluvium formed at the mouth of a river where the deposition of some of its load exceeds its rate of removal, crossed by the divergent chan-nels (distributaries) of the river IT: alluvial fan, bay delta, canyon delta, fan, fan delta, outwash, outwash plain*	SDTS
Fan	a gently sloping fan shaped feature usually found near the lower termination of a canyon	DIGEST
Alluvial fans	Fan-shaped deposits of alluvium (river or stream-bed sediment). UF: fans (alluvial) R: deltas, floodplains NT: – BT: physiographic features	AFTT

Tentative landform elements

Category	Definition, context	Source
Slope, incline, side	an elevated geological formation HR: (geological) formation → (physical) object HO: ascent, acclivity, rise, raise, climb, upgrade (an upward slope or grade (as in a road)), bank (sloping land (especially the slope beside a body of water), bank, cant, camber (a slope in the turn of a road or track; the outside is higher than the inside in order to reduce the effects of centrifugal force), canyonside (the steeply sloping side of a canyon), coast (a slope down which sleds may coast), descent, declivity, fall, decline, declination, declension, downslope (a downward slope or bend), escarpment, scarp (a long steep slope or cliff at the edge of a plateau or ridge; usually formed by erosion), hillside (the side or slope of a hill), mountainside, versant (the side or slope of a mountain), ski slope (a snow-covered slope for skiing) HN: (part) natural elevation (a raised or elevated geological formation) MN: –	WNET
Slope	a piece of rising or falling ground	OSHO
SlopedArea	a SlopedArea is a land surface which lies at an angle to the horizontal so that some points on it are higher than other, a slope SC: LandForm	SUMO-G
Slope category	an area enclosing a group of slope values falling within a set range	DIGEST
Talus, scree	a sloping mass of loose rocks at the base of a cliff HR: (geological) formation → (physical) object HO, HN, MN: –	WNET
Talus	slopes of broken rock debris on a mountainside	SDTS
Cliff, drop, drop-off	a steep high face of rock HR: (geological) formation → (physical) object HO: crag (a steep rugged rock or cliff), precipice (a very steep cliff) HN, MN: –	WNET
Cliff	a high, steep, or overhanging face of rock IT: beach scarp, bluff°, ceja, crag*, escarpment, ice cliff, marine cliff, palisade, precipice*, scar*, scarp, scaw	SDTS
Cliff	a steep rock face	OSHO
Bluff/cliff/escarpment	a steep, vertical, or overhanging face of rock or earth, see also 'fault'	DIGEST
Cliffs	high vertical, near-vertical, or overhanging faces of rock, earth, or ice UF: bluffs, clefts, escarpments, precipices, scraps R: canyons, ledges, ridges NT: – BT: physiographic features	AFTT
Cliff	a Cliff is any high, very-steep-to-perpendicular or overhanging face of rock or earth, a precipice SC: SlopedArea	SUMO-G
Escarpment	a long steep slope at the edge of a plateau	OSHO
Wall	a vertical (or almost vertical) smooth rock face (as of a cave or mountain) HR: (geological) formation → (physical) object HO: – HN: (part) cave (a geological formation consisting of an underground enclosure with access from the surface of the ground or from the sea) MN: –	WNET
Bluff	a high steep bank (usually formed by river erosion) HR: bank → ridge → (natural) elevation → (geological) formation → (physical) object HO, HN: – MN: (inherited) slope, incline, side	WNET
Terrace, bench	a level shelf of land interrupting a declivity (with steep slopes above and below) HR: tableland, plateau → highland, upland → (natural) elevation → (geological) formation → (physical) object HO, HN, MN: –	WNET
Terrace	a step-like feature between higher and lower ground: a relatively flat or gently inclined shelf of earth, backed and fronted by steep slopes or man-made retaining walls IT: bench, kame terrace, marine bench, raised beach, rock terrace	SDTS
Peak, crown, crest, top, tip, summit	the top point of a mountain or hill HR: topographic point, place, spot → point → location → (physical) object HO: hilltop, brow (the peak of a hill), pinnacle (a lofty peak), mountain peak (the summit of a mountain) HN, MN: –	WNET
Hilltop, brow	the peak of a hill HR: peak, crown, crest, top, tip, summit → topographic point, place, spot → point → location → (physical) object HO, HN, MN: –	WNET
Pinnacle	a lofty peak HR: peak, crown, crest, top, tip, summit → topographic point, place, spot → point → location → (physical) object HO, HN, MN: –	WNET
Mountain peak	the summit of a mountain HR: peak, crown, crest, top, tip, summit → topographic point, place, spot → point → location → (physical) object HO: – HN: (part) mountain, mount (a land mass that projects well above its surroundings; higher than a hill) MN: –	WNET
Peak	the summit of a mountain IT: ice peak, nunatak, seapeak, summit	SDTS

Category	Definition, context	Source
Mountain summits	peaks of mountains UF: ahus, mountain crests, nunataks, peaks, summits R: ridges NT: – BT: mountains	AFTT
Ridge, ridgeline	a long narrow range of hills HR: (geological) formation → (physical) object HO: arete (a sharp narrow ridge found in rugged mountains), hogback, horseback (a narrow ridge of hills) HN, MN: –	WNET
Ridge	a long narrow natural elevation or striation HR: (natural) elevation → (geological) formation → (physical) object HO: bank; bar; dune, sand dune; esker; ledge, shelf; reef; ripple mark HN: – MN: (inherited) slope, incline, side	WNET
Ridge	a long narrow natural elevation on the floor of the ocean HR: (geological) formation → (physical) object HO: Mid-Atlantic Ridge (a very long narrow elevation on the ocean floor that runs all the way from Iceland in the North Atlantic to Bouvet Island in the South Atlantic) HN, MN: –	WNET
Ridge	a long and narrow upland with steep sides IT: arete, beach cusps, beach ridge, cerro*, crest, cuesta*, drumlin*, esker, kame*, range*°, sand dune*, sand hills*, sill*, spur°, volcanic dike	SDTS
Ridges	elevations with a narrow elongated crest which can be part of a hill or mountain UF: aretes, beach ridges, cuestas, eskers, hogbacks, icecap ridges, rises (seafloor), spurs (physiographic) R: cliffs, mountain summits, seafloor features NT: drumlins BT: mountains	AFTT
Mountain pass	a natural route through a low place in a mountain range	DIGEST
Gap	low point or opening between hills or mountains or in a ridge or mountain range IT: col, defile*, mountain pass, notch*, pass°, saddle, sill*	SDTS
Gaps	ravines or gorges cut deeply through mountain ridges, or between hills or mountains UF: cols, defiles, passes, saddles (physiographic), sills (physiographic) R: valleys NT: – BT: physiographic features	AFTT

Remaining categories

The following categories are not easily fitted to any of the above superordinate categories. Nevertheless, they are listed here for completeness. Some of the categories could be understood as general superordinate categories to some landform (element) categories, e.g. *tectonic features* or *volcanic features*. Others like *karst areas* are close to other higher level compositions/ juxtaposition like *mountain range* (which is pointed out in Fig. 29 on page 116 in Section 3.4.5 of this thesis depicting the landform taxonomy). However, *karst areas* probably leaves too much ambiguity regarding the features which may be present therein.

Category	**Definition, context**	**Source**
Large isolated rock, boulder, or rocky formation	a conspicuous isolated rocky formation or single large stone existing in its entirety above the high water mark. From offshore it would appear to a mariner as a single point on land and would be appropriate for use in navigation.	DIGEST
Natural rock formations	naturally formed topographic features, commonly differing conspicuously from adjacent objects or material UF: crags, pillars (natural formation), pinnacles (natural formation), rock towers, rocks R: – NT: arches (natural formation) BT: physiographic features	AFTT
Rock strata/rock formation	a visual topographic outcrop, layers or beds of rock	DIGEST
Crevice/crevasse	a narrow fissure, crack, or rift in the Earth's surface, snow or ice	DIGEST
Geothermal feature	a terrain surface feature controlled by or derived from the heat of the Earth's interior	DIGEST
Fumarole	a hole in the Earth's crust from which steam and gases are emitted	SDTS
Miscellaneous obstacle	obstacle feature which is of a minor nature and which is not covered by another feature coding in this specification	DIGEST
US-potential landslide area, UK-landslide/scree	a mass of land, with a high potential of slipping down from a mountain, hill, etc.	DIGEST
Landslide	the mass of earth or rock which has slipped down from a mountain or cliff	DIGEST
Undermined land	area undermined through mining activities that has already partly subsided or that is in the process of subsiding	DIGEST
Karst areas	areas of geologic formations of irregular limestone deposits with sinks, underground streams, and caverns UF, R, NT: – BT: physiographic features	AFTT
Badlands	areas characterized by a maze of very closely spaced, deep, narrow, steep-sided ravines, and sharp crests and pinnacles UF: – R: barren lands, canyons, deserts NT: – BT: physiographic features	AFTT
Mineral deposit areas	areas where masses of naturally occurring mineral material are found, e.g. metal ores or nonmetallic minerals UF: coal fields, coalfields, lodes (mineral), petroleum basins, placers, salt deposit areas R: basins, mine sites NT: – BT: physiographic features	AFTT
Tectonic features	features resulting from structural deformation of the earth's crust through tectonic processes UF, R: – NT: earthquake features, faults, folds (geologic) (all not listed here) BT: physiographic features	AFTT
Volcanic features	features formed from those igneous rocks that have reached or nearly reached the Earth's surface before solidifying UF: crater lakes, dykes (geologic) R: – NT: lava fields, volcanoes (all not listed here) BT: physiographic featuers	AFTT
Thermal features	holes in the Earth's crust from which hot water and steam (geysers), and gases and vapors (fumaroles) are emitted UF: fumaroles, geysers, hot springs R, NT: – BT: hydrographic features	AFTT
Lava fields	areas of formations resulting from the consolidation of molten rock on the surface of the Earth UF: lava areas R, NT: – BT: volcanic features	AFTT

Appendix D: PHP code for the questionnaire

PHP code for the questionnaire: *questionnaire_db.php*

```
<?php /* BEGIN OF PHP SCRIPT */
include("./conf.php");

$uid = time();

// Make connection, select appropriate database
$link = mysql_connect($ip, $username, $password) or
  die ("No connection can be obtained: " . mysql_error());
mysql_select_db($database) or
  die ("Selection of database failed");

// Execute SQL query
$query = "SELECT * FROM valley_questions";
$result = mysql_query($query) or die("Query failed: " . mysql_error());

/* Build array from output of a SQL query, using column
names as indices instead of simple enumeration of columns */
mysql_data_seek($result, 0);
$n = 0;
while($line = mysql_fetch_array($result, MYSQL_ASSOC)){
  foreach($line as $key => $col_value){
    $caption_info[$n][$key] = $col_value;
  }
  $n += 1;
}

// Randomise the order of the questions
shuffle($caption_info);

// Free the result
mysql_free_result($result);

// Close the connection
mysql_close($link);

/* END OF PHP SCRIPT */ ?>

<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 4.01 Transitional//EN" "http://www.w3.org/TR/html4/loose.dtd">
<html>
  <head>
    <title>&quot;Valleyness&quot; experiment</title>
    <style type="text/css">
        a:link { border:none; text-decoration:none; font-weight:bold; color:#009; }
     a:visited { border:none; text-decoration:none; font-weight:bold; color:#009; }
      a:active { border:none; text-decoration:none; font-weight:bold; background-color:#cff; }
       a:hover { border:none; text-decoration:none; font-weight:bold; color:#007FFF; }
       a:focus { border:none; text-decoration:none; font-weight:bold; color:#007FFF; }
          body { margin-left:50px; margin-right:50px; margin-top:50px; margin-bottom:100px;
                 font-family:"Helvetica Neue", Arial, Helvetica, sans-serif; color:#3D3D3D;
                 background-color:white; }
            h1 { font-size:3em;line-height:1;margin-bottom:0.5em; }
            h2 { font-size:2em;margin-bottom:0.75em; }
            h3 { font-size:1.5em;line-height:1;margin-bottom:1em; }
            h4 { font-size:1.2em;line-height:1.25;margin-bottom:1.25em; }
             p { margin:0 0 1.5em; }
    </style>
  </head>



  <body>
    <!-- INTRODUCTION-->
    <div align="justify" id="intro">
      <h1>&quot;Valleyness&quot; experiment</h1>
      <h3>Description of the &quot;valleyness&quot; of a location judged from an image</h3>
      <br>
      <p>Our research project is exploring ways to improve the conceptualisation and
         representation of landforms in Geographic Information Systems. As part of this
```

```
    project we are investigating different automatically derived measures of
    &quot;valleyness&quot; for locations.</p>
  <p>We would like to ask you to support this work by answering the following
    questionnaire. It should only take around 15 minutes to complete.</p>
  <p>Before you start the exercise we will collect some demographic information. These
    data will <i>not</i> be used to identify you and we will not disclose any personal
    information to any third parties.</p>
  <p>In the experiment we would like you to look at a set of pictures showing landscapes
    from different regions in Switzerland. Please rate for each picture <b>the degree to
    which you think that the photographer was in a valley when taking the picture</b>.
    Note that there are no right or wrong answers - we are interested in your opinion on
    the picture. We would like to thank you in advance for your help.</p>
  <p>We have tested the questionnaire on Firefox, Internet Explorer and Safari - if you
    encounter any problems, please let us know. If you need any other assistance or have
    questions while taking this survey, please contact:</p>
  <p><b>Ralph Straumann</b><br>
    Department of Geography - University of Zurich<br>
    Winterthurerstrasse 190<br>
    CH-8057 Zurich<br>
    +41 (0)44 635 51 98<br>
    <a href="mailto:ralph.straumann@NO.SPAM.geo.uzh.NO.SPAM.ch">ralph.straumann@
      <span style="display:none;">no.spam.</span>geo.uzh.<span style="display:none;">
      no.spam.</span>ch</a></p>

  <a href="http://cheese.geo.unizh.ch:30322/valley_expt/expt_de/questionnaire_db.php">
   Deutschsprachige Version dieses Fragebogens (German version)</a>
  <br><br><br>
  <a href="#personal">Start the experiment...</a>
  <br><br><br><br><br><br><br><br><br><br><br><br><br><br><br>
  <br><br><br><br><br><br><br><br><br><br><br><br><br><br><br>
</div>

<!-- PERSONAL DETAILS-->
<form name="idform" method="post" action="./write_form_db.php">
<div id="personal">
  <?php
    // Add UID to form using PHP
    echo "<input type=\"hidden\" name=\"uid\" value=\"".$uid."\">";
  ?>
  <input type="hidden" name="language" value="en">
  <br>
  <h3>Personal details</h3>

  <p><b>Gender</b><br>
    <input type="radio" name="gender" value="female"> female<br>
    <input type="radio" name="gender" value="male"> male<br>
  </p>

  <p><b>Age</b><br>
    <input type="radio" name="age" value="<20"> &lt;20<br>
    <input type="radio" name="age" value="20-29"> 20-29<br>
    <input type="radio" name="age" value="30-39"> 30-39<br>
    <input type="radio" name="age" value="40-49"> 40-49<br>
    <input type="radio" name="age" value="50-59"> 50-59<br>
    <input type="radio" name="age" value=">=60"> &ge;60<br>
  </p>

  <p><b>Occupation</b><br>
    <input type="text" size="40" maxlength="40" name="occupation"><br><br>
    <input type="radio" name="researcher" value="researcher"> I am a researcher in the
      field of geosciences (e.g. geography, geomorphology, geomorphometry, ...).<br>
    <input type="radio" name="researcher" value="student"> I am a student in the field
      of geosciences (e.g. geography, geomorphology, geomorphometry, ...).<br>
    <input type="radio" name="researcher" value="layperson"> I am neither of the
      above.<br>
  </p>

  <p><b>Town and country of residence</b><br>
    <input type="text" size="40" maxlength="40" name="residence">
  </p>
  <br><br><br>

  <p><a href="#1">Go to questions</a></p>
```

```
  <br><br><br><br><br><br><br><br><br><br><br><br><br><br>
  <br><br><br><br><br><br><br><br><br><br><br><br><br><br>
</div>


<!-- IMAGE DESCRIPTION EXPERIMENT-->
<?php // BEGIN OF PHP SCRIPT
  // Set up a random variable used for the questionGroup switching
  $random = rand(1,4);

  // Add questionGroup information to form using PHP
  echo "<input type=\"hidden\" name=\"questionGroup\" value=\"".$random."\">";

  $index = 1;
  for($i=0; $i < sizeof($caption_info); $i++){
    $questionnaire_data = $caption_info[$i];
    // Write out the image
    $imageURL = $questionnaire_data["imageURL"];
    $imageCode = $questionnaire_data["imageCode"];
    $questionGroup = $questionnaire_data["questionGroup"];

    /* Set up the switch for the questionGroups (4 groups of 25 questions/images each).
       Attribute questionGroup has values [1, 4] */
    if($random == $questionGroup){
      echo "<div id=\"".$index."\">";
      echo "<h3>Valleyness estimation (".$index." of 25)</h3>";

      echo "<img src=\"".$imageURL."\" alt=\"Questionnnaire image\">\n";
      echo "<br>";
      echo "<br>";
      echo "For the above picture, rate the &quot;valleyness&quot; of the
            <b>photographer&apos;s location</b>, where 5 is definitely in a valley and 1
            is definitely NOT in a valley: <BR>\n";
      echo "<INPUT type=\"radio\" name=\"pic".$imageCode."\" value=\"5\">5 (definitely in
            a valley)<BR>\n";
      echo "<INPUT type=\"radio\" name=\"pic".$imageCode."\" value=\"4\">4 <BR>\n";
      echo "<INPUT type=\"radio\" name=\"pic".$imageCode."\" value=\"3\">3 <BR>\n";
      echo "<INPUT type=\"radio\" name=\"pic".$imageCode."\" value=\"2\">2 <BR>\n";
      echo "<INPUT type=\"radio\" name=\"pic".$imageCode."\" value=\"1\">1 (definitely NOT
            in a valley)<BR>\n";
      echo "<br>";
      echo "<INPUT type=\"radio\" name=\"pic".$imageCode."\" value=\"99\">? From this
            picture <b>I cannot estimate &quot;valleyness&quot;</b>.<BR>\n";
      echo "<br>";

      if($index < 25){
        echo "<br><p><a href=\"#".($index+1)."\">Go to next question</a> (".($index+1)."
              of 25)</p>";
        echo "</div>";
        echo "<br><br><br><br><br><br><br><br><br><br><br><br><br><br><br><br><br><br><br>
              <br><br><br><br><br><br><br><br><br>";
      }
      else{
        echo "<br><br>";
        echo "<h3>Many thanks for taking part in the survey, please click on the submit
              button below.</h3>";
        echo "If you are interested in getting feedback on the eventual results of this
              study, please enter your e-mail address in the box below:<br><br>";
        echo "<input type=\"text\" size=\"50\" maxlength=\"50\" name=\"mailAddress\">
              <br><br>";
        echo "Your e-mail address will be saved independently from your questionnaire
              results and will not be disclosed nor used for anything other than
              contacting you regarding the results of the study.<br><br>";
        echo "On submitting your results you will be redirected to a confirmation page.
              <br><br>";

        echo "<input name=\"Submit\" type=\"submit\" value=\"Submit\">";
        echo "</div>";
      }
      $index++;
    } // end of question group switch
  } // end of for loop
/* END OF PHP SCRIPT */ ?>
```

```
    </form>
  </body>
</html>
```

PHP code for saving the questionnaire data in the database and confirming: *write_form_db.php*

```
<?php
include("./conf.php");

// Determine if the form was sent through get method or post method.
if($_POST){ $array = $_POST; }
else if($_GET){ $array = $_GET; }
else{ die("<h3>You must access this file through a form.</h3>"); }

// Get the current time for analysis how long it took participant to fill in questionnaire
$completed = time();

$keys = array_keys($array);
$cr = "\n";

// We need to assemble an SQL insertion statement
$fields = "";
foreach($keys as $key){
  $data = $data.$key."=".$array[$key]."&";

  /* Get the questionGroup value in order to increment the respective counter in table
     valley_expt automatically */
  if($key == "questionGroup"){
    $questionGroup = $array[$key];
  }

  /* Get the mailAddress value in order to insert the e-mail address of people interested in
     follow-up in an table which is independent from valley_results in order to guarantee
     anonymity. */
  if($key == "mailAddress"){
    $mailAddress = $array[$key];
  }


  if($key != "success" && $key != "Submit" && $key != "mailAddress"){
    $field = $key;
    $value = $array[$key];

    if ($fields == ""){
      $fields = $fields." `".$field."' ";
      $values = $values." `".$value."' ";
    }
    else{
      $fields = $fields.", `".$field."' ";
      $values = $values.", `".$value."' ";
    }
  }
}

$query = "INSERT INTO 'valley_results' (". $fields.", completed) VALUES (".$values.",
  ".$completed.");";

// Formulate the query to increment the questionGroup counter in table valley_expt
$query2 = "UPDATE 'valley_expt' SET number".$questionGroup." = number".$questionGroup." + 1;";

// Formulate the query to insert the given e-mail address into table interested_people
$query3 = "INSERT INTO 'interested_people' (mailAddress) VALUES (\"$mailAddress\");";

$success = $array['success'];
$error = $array['error'];

mysql_connect($ip, $username, $password);
mysql_select_db($database) or die ("<h3>Unable to select database</h3>");

$result = mysql_query($query) or
  die ("<h3>Database problem (insertion of questionnaire values): ". mysql_error()."</h3>");;
$result = mysql_query($query2) or
```

```
  die ("<h3>Database problem (incrementation of questionGroup counter): ". mysql_error()."
        </h3>");;
$result = mysql_query($query3) or
  die ("<h3>Database problem (insertion of mailAddress into anonymous table): ".
        mysql_error()."</h3>");;

mysql_close(); ?>
<html>
  <head>
    <title>&quot;Valleyness&quot; experiment</title>
    <style type="text/css">
           a:link { border:none; text-decoration:none; font-weight:bold; color:#009; }
        a:visited { border:none; text-decoration:none; font-weight:bold; color:#009; }
         a:active { border:none; text-decoration:none; font-weight:bold;
                    background-color:#cff; }
          a:hover { border:none; text-decoration:none; font-weight:bold; color:#007FFF; }
          a:focus { border:none; text-decoration:none; font-weight:bold; color:#007FFF; }
             body { margin-left:50px; margin-right:50px; margin-top:50px; margin-bottom:100px;
                    font-family:"Helvetica Neue", Arial, Helvetica, sans-serif; color:#3D3D3D;
                    background-color:white; }
               h1 { font-size:3em;line-height:1;margin-bottom:0.5em; }
               h2 { font-size:2em;margin-bottom:0.75em; }
               h3 { font-size:1.5em;line-height:1;margin-bottom:1em; }
               h4 { font-size:1.2em;line-height:1.25;margin-bottom:1.25em; }
                p { margin:0 0 1.5em; }
    </style>
  </head>
  <body>
    <div align="justify">
      <h3>&quot;Valleyness&quot; experiment: Confirmation</h3>
      <br>
      <p>The database has received the content of your questionnaire. Thank you very much
         again for your time and your participation!<br>
         We look forward to interesting results.</p>
      <p>If you wish, you may proceed to the website of the <a href="http://www.geo.uzh.ch">
         Department of Geography at the University of Zurich</a></p>
      <p>Best wishes, <br><br>
         <b><a href="http://www.geo.uzh.ch/~rsm">Ralph Straumann</a></b>
      </p>
    </div>
  </body>
</html>
```

Database for valleyness questionnaire

Table valley_expt

Attribute	Type	Domain	Description
number1	Integer	–	Number of submitted questionnaires of questionGroup 1
number2	Integer	–	Number of submitted questionnaires of questionGroup 2
number3	Integer	–	Number of submitted questionnaires of questionGroup 3
number4	Integer	–	Number of submitted questionnaires of questionGroup 4

Table valley_questions

Attribute	Type	Domain	Description
imageURL	Text	–	URL of the images used in the questionnaire
imageCode	Text	–	UID of the image
questionGroup	Integer	{1, 2, 3, 4}	The questionGroup the image belongs to

Table valley_results

Attribute	Type	Domain	Description
uid	Integer	–	UID of the questionnaire records (timestamp upon questionnaire loading)
completed	Integer	–	Timestamp upon questionnaire submission
researcher	Text	{researcher, student, layperson, null}	Expertise of the questionnaire participant
language	Text	{en, de}	Language in which the participant took the questionnaire
gender	Text	{female, male, null}	Gender of the participant
age	Text	{<20, 20-29, 30-39, 40-49, 50-59, ≥60, null}	Age of the participant
occupation	Text	–	Occupation of the participant
residence	Text	–	Town and country of residence of the participant
questionGroup	Integer	{1, 2, 3, 4}	The questionGroup the participant answered
followed by hundred entries of the form:			
pic####	Integer	{1, 2, 3, 4, 99, null}	Participant's rating of image with UID ####

Table interested_people

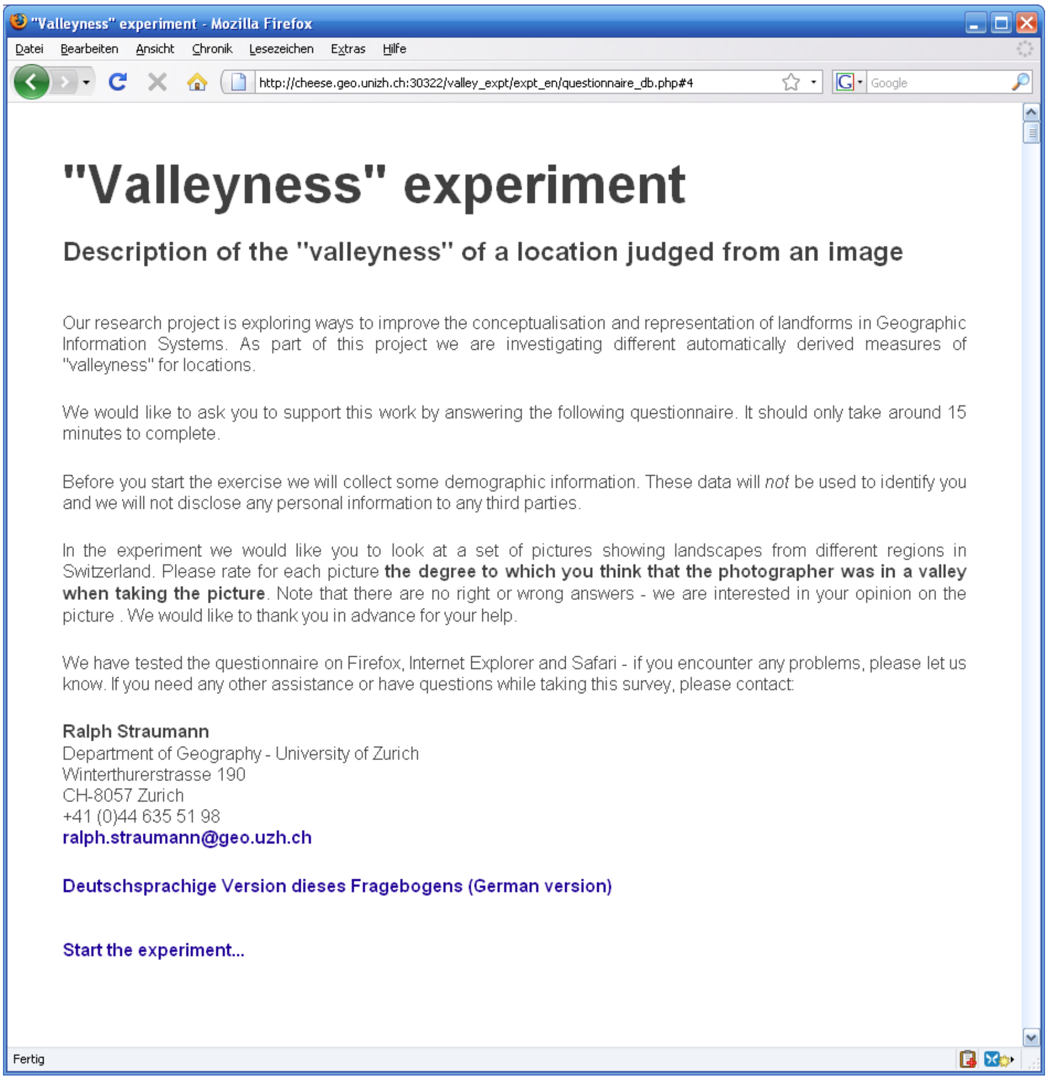
Attribute	Type	Domain	Description
mailAddress	Text	{anything, null}	E-mail address of interested participants (if provided)

Appendix E: The “Valleyness” experiment

This appendix presents the structure of the questionnaire employed in the study about valleyness (Chapter 6) as well as the spatial distribution of questionnaire participants at a coarse level.

Questionnaire

Introduction and explanation of the experiment (the text of this introduction to the experiment is printed in both English and German on the following two pages):



"Valleyness" experiment

Description of the "valleyness" of a location judged from an image

Our research project is exploring ways to improve the conceptualisation and representation of landforms in Geographic Information Systems. As part of this project we are investigating different automatically derived measures of "valleyness" for locations.

We would like to ask you to support this work by answering the following questionnaire. It should only take around 15 minutes to complete.

Before you start the exercise we will collect some demographic information. These data will *not* be used to identify you and we will not disclose any personal information to any third parties.

In the experiment we would like you to look at a set of pictures showing landscapes from different regions in Switzerland. Please rate for each picture **the degree to which you think that the photographer was in a valley when taking the picture**. Note that there are no right or wrong answers - we are interested in your opinion on the picture . We would like to thank you in advance for your help.

We have tested the questionnaire on Firefox, Internet Explorer and Safari - if you encounter any problems, please let us know. If you need any other assistance or have questions while taking this survey, please contact:

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+41 (0)44 635 51 98
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Deutschsprachige Version dieses Fragebogens (German version)

Start the experiment...

"Valleyness" experiment

Description of the "valleyness" of a location judged from an image

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Deutschsprachige Version dieses Fragebogens (German version)

Start the experiment...

"Talhaftigkeits"-Experiment

Beschreibung der "Talhaftigkeit" eines Orts

Unser Forschungsprojekt sucht Möglichkeiten, die Konzeptualisierung und die Repräsentation von Landformen in Geographischen Informationssystemen zu verbessern. Als Teil dieses Projekts untersuchen wir verschiedene, automatisch abgeleitete Masse für die "Talhaftigkeit" von Orten.

Wir bitten Sie, unsere Forschung zu unterstützen, indem Sie den folgenden Fragebogen ausfüllen. Das Ausfüllen beansprucht circa 15 Minuten.

Bevor Sie zum eigentlichen Fragen-Teil gelangen, bitten wir Sie um einige demographische Angaben. Diese Daten werden *nicht* dazu benutzt, Sie zu identifizieren und wir werden gegenüber Drittparteien keinerlei persönliche Informationen veröffentlichen.

Im Experiment bitten wir Sie, sich eine Auswahl von Fotografien von Landschaften aus verschiedenen Regionen der Schweiz anzuschauen. Bitte bewerten Sie für jedes Bild, **zu welchem Grad der Fotograf in einem Tal war, als er die Aufnahme machte**. Bitte bedenken Sie: Es gibt keine richtigen oder falschen Antworten - wir sind an Ihrer Meinung zu den einzelnen Bildern interessiert. Für Ihre Mithilfe danken wir Ihnen im Voraus.

Wir haben diesen Fragebogen auf Firefox, Internet Explorer und Safari gestestet. Kontaktieren Sie uns bitte, falls Sie auf Probleme stossen. Auch falls Sie anderweitig Unterstützung brauchen oder Fragen zur Beantwortung des Fragebogens haben, kontaktieren Sie bitte:

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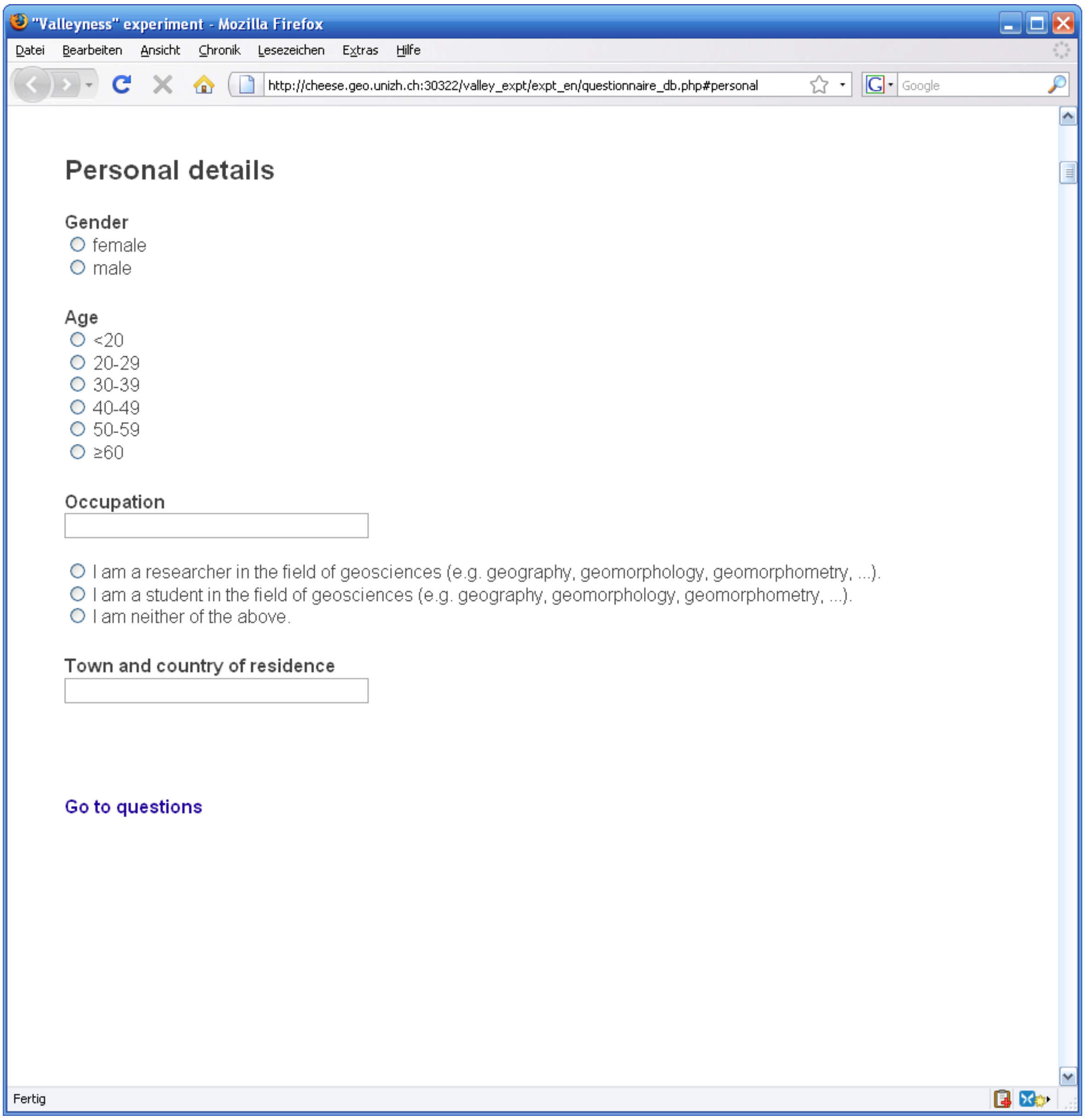
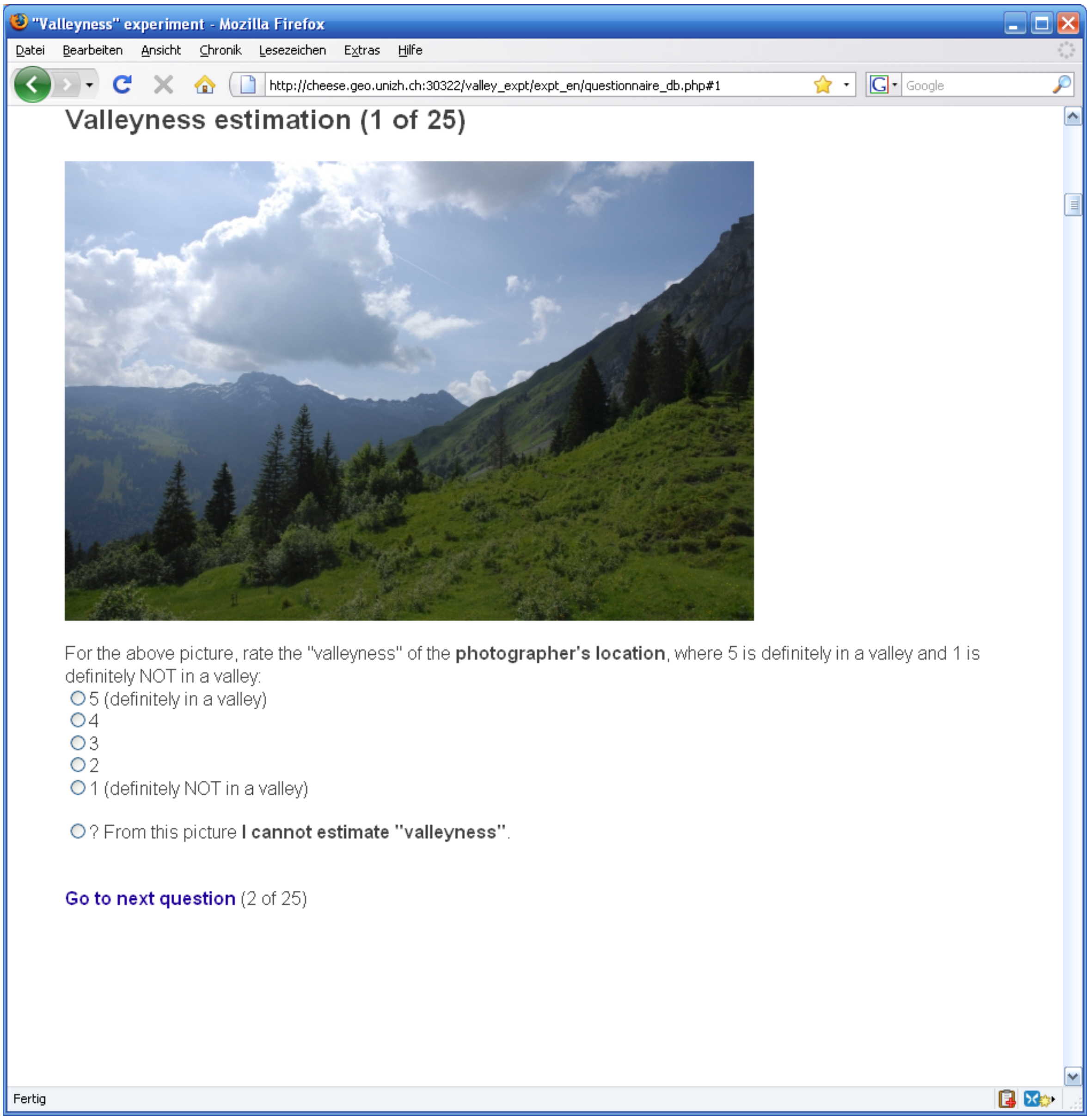
English version of this questionnaire

Starte das Experiment...

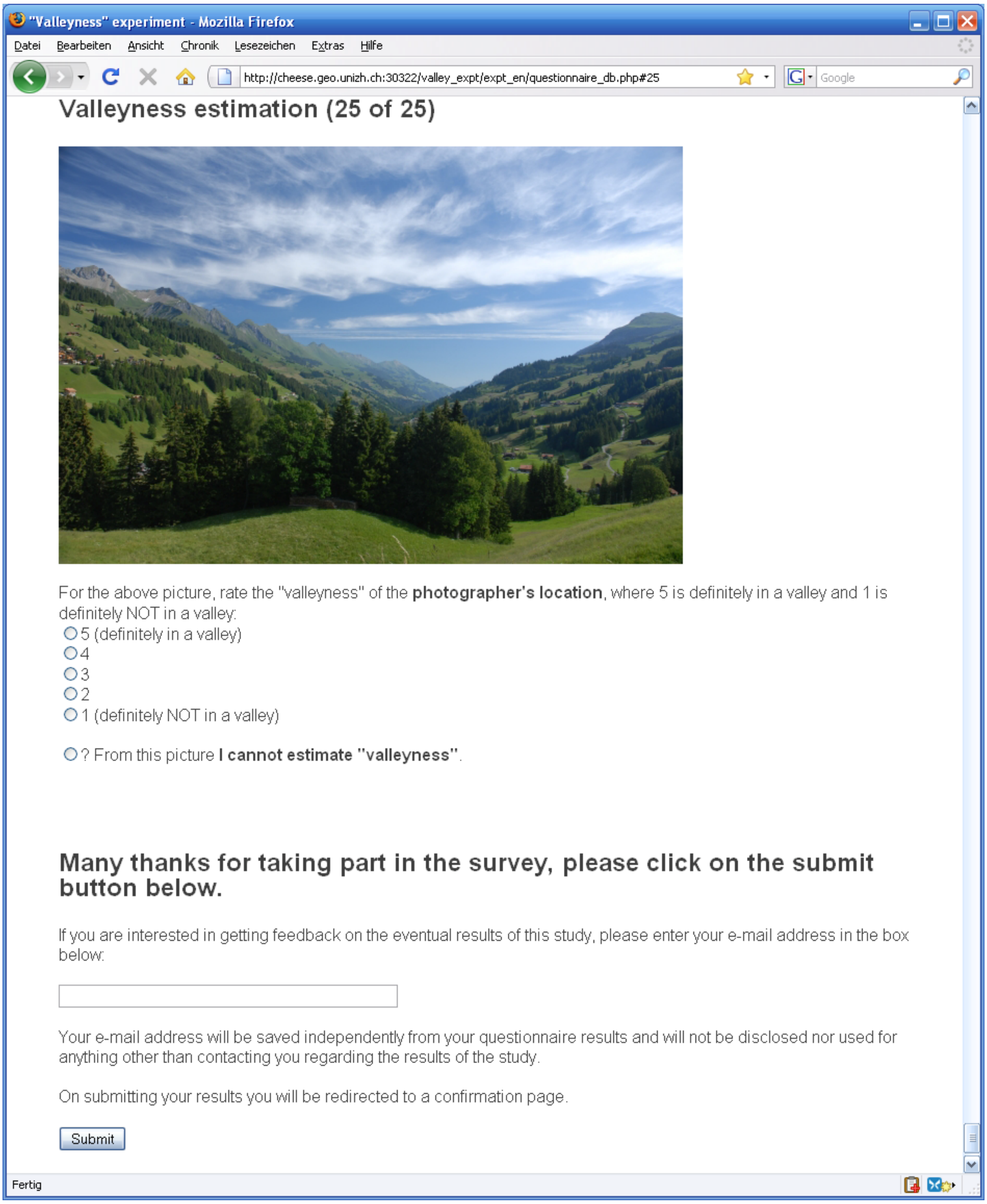
Opening questions regarding personal details:



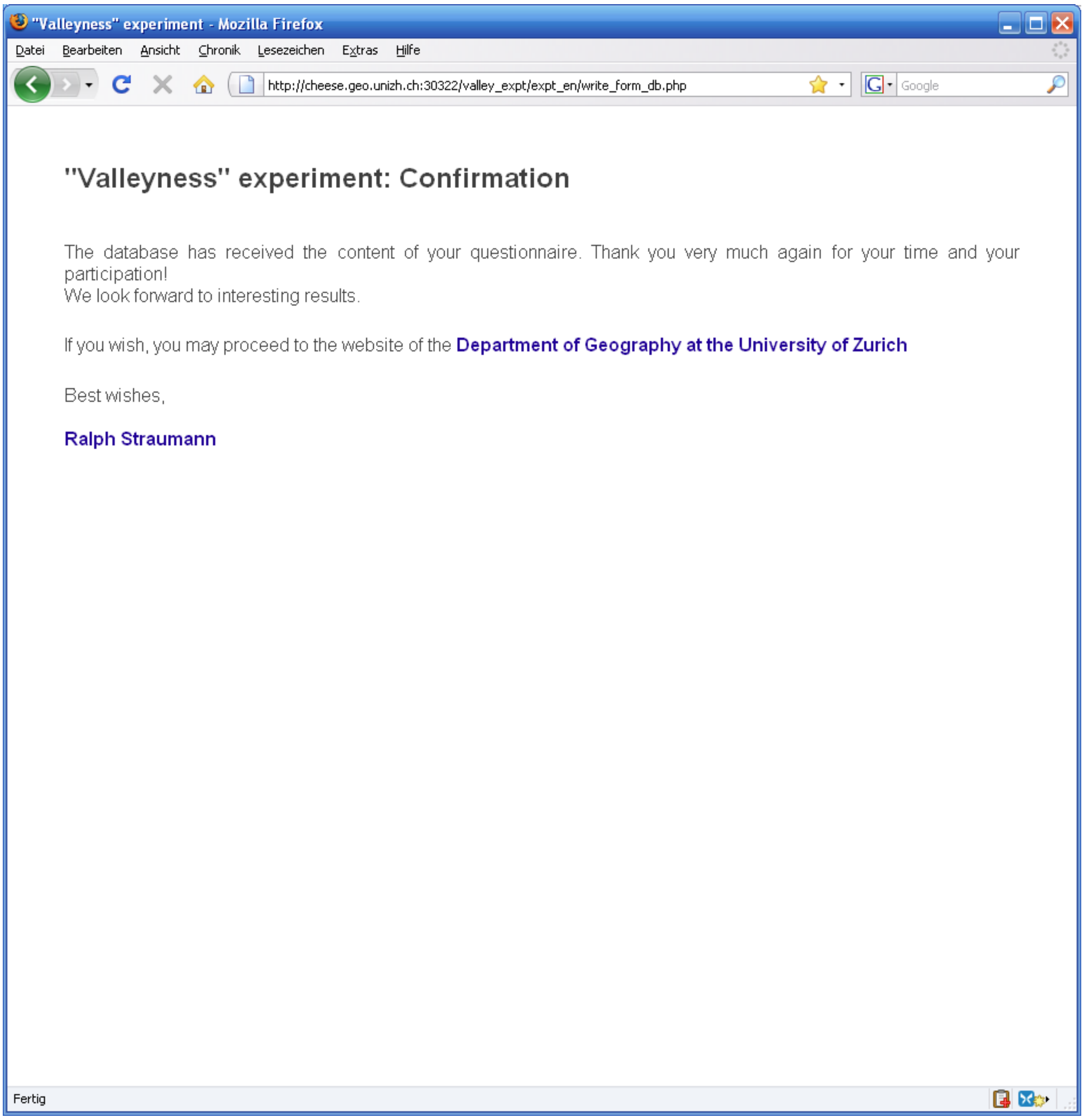
Example of a "valleyness" question using a stimulus image (25 such questions were posed to the participant):



The last question of the questionnaire (25th) with the footer of the questionnaire asking the participant to provide an e-mail address if he or she is interested in follow-up information and the submit button:



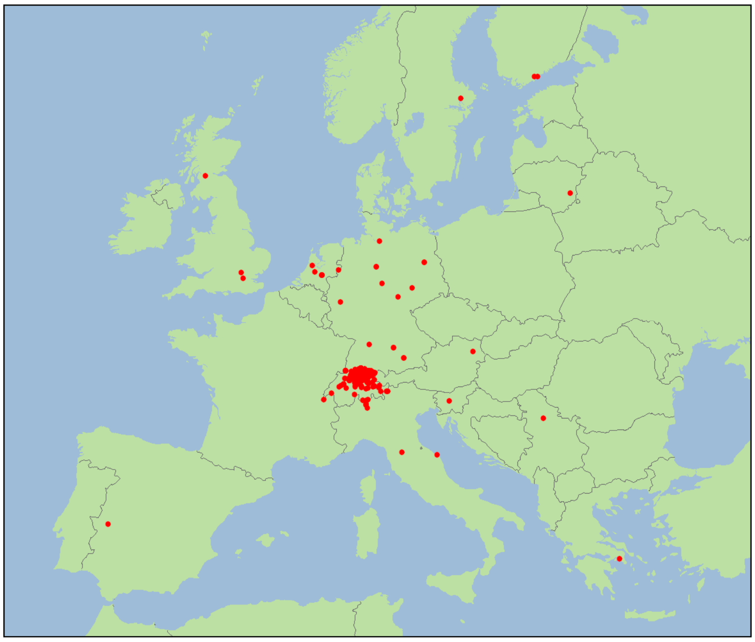
The confirmation page displayed to the participant after completion of the questionnaire and successful saving of the data:



Spatial distribution of questionnaire participants

Places of residence of questionnaire participants on a global basemap:

Places of residence of questionnaire participants in Europe:



Appendix F: Detailed stimulus considerations

This section presents an in-depth investigation into groups of stimuli. The groups were generated based on characteristics of answers of questionnaire participants.

In order to further elucidate potential factors influencing the valleyness estimates by questionnaire participants and in order to further elucidate some properties of valleyness perceived through the stimulus images, the latter were analysed with respect to several questions. In the following section the stimuli with the highest and lowest associated valleyness, with the highest and lowest spread of associated valleyness and with the highest and lowest proportion of "non-answers" in the estimation are presented.

The first two groups of highest and lowest valleyness stimuli were selected based upon v_{median}. Highest and lowest spread for the second two groups was operationalised through the standard deviation of the participants' answers. The proportion of "non-answers" (i.e. the proportion of people opting for "from this picture I cannot estimate valleyness" in the questionnaire) for the third pair of groups equates to rV_{99} (see equation 18 in Section 6.4.3 of this thesis).

Under every picture the respective ID is indicated. In order to address a particular image or set of images, this ID is referred to in the text of the following section in square brackets "[ ]". In all groups of images the ID is accompanied by the most important data regarding questionnaire and the valleyness algorithm:

- v_{median} median valleyness estimate from questionnaire
- v_{mean} mean valleyness estimates
- v_{std} standard deviation of valleyness estimates
- rV_{99} proportion of "non-answers" ("from this picture I cannot estimate valleyness")
- v_{patch} combined valleyness calculated on a per drainage sub-basin patch basis
- v_{basin} combined valleyness calculated on a per drainage sub-basin basis
- u uncertainty as defined in Section 6.4.5 of this thesis

Stimuli with highest valleyness. The following group of photographs represents stimulus images with $v_{median} \geq 4$ (where only [4963] has v_{median} of 5). After v_{median} the images are sorted according to v_{mean} in descending order.

Almost all images have an upward-looking perspective and in all images (maybe with the exception of [1589]) a significant amount of landmass is visible which is positioned at a clearly higher altitude then the observer point.

4963

v_{median}: 5; v_{mean}: 4.52; v_{std}: 0.79; rV_{99}: 0.5%
u: 0.08; v_{patch}: 0.91; v_{basin}: 0.91

1792

v_{median}: 4; v_{mean}: 4.17; v_{std}: 0.96; rV_{99}: 2.3%
u: 0.20; v_{patch}: 0.53; v_{basin}: 0.53

4286

v_{median}: 4; v_{mean}: 4.14; v_{std}: 1.05; rV_{99}: 0.5%
u: 0.20; v_{patch}: 1.00; v_{basin}: 0.97

642

v_{median}: 4; v_{mean}: 3.99; v_{std}: 1.02; rV_{99}: 3.7%
u: 0.26; v_{patch}: 0.96; v_{basin}: 0.96

366

v_{median}: 4; v_{mean}: 3.7; v_{std}: 1.07; rV_{99}: 2.8%
u: 0.26; v_{patch}: 1.00; v_{basin}: 0.99

2984

v_{median}: 4; v_{mean}: 3.63; v_{std}: 1.16; rV_{99}: 6.9%
u: 0.40; v_{patch}: 1.00; v_{basin}: 0.99

1927

v_{median}: 4; v_{mean}: 3.57; v_{std}: 1.06; rV_{99}: 5.2%
u: 0.32; v_{patch}: 0.59; v_{basin}: 0.63

323

v_{median}: 4; v_{mean}: 3.44; v_{std}: 1.22; rV_{99}: 1.6%
u: 0.30; v_{patch}: 0.12; v_{basin}: 0.92

2153

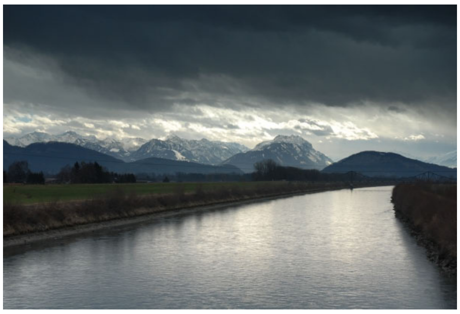
v_{median}: 4; v_{mean}: 3.43; v_{std}: 1.13; rV_{99}: 2.6%
u: 0.28; v_{patch}: 0.91; v_{basin}: 0.90

3428

v_{median}: 4; v_{mean}: 3.42; v_{std}: 1.29; rV_{99}: 0.5%
u: 0.30; v_{patch}: 0.88; v_{basin}: 0.83

1589

v_{median}: 4; v_{mean}: 3.37; v_{std}: 1.43; rV_{99}: 9.6%
u: 0.59; v_{patch}: 0.98; v_{basin}: 0.99



2026

v_{median}: 4; v_{mean}: 3.37; v_{std}: 1.45; rV_{99}: 2.4%
u: 0.41; v_{patch}: 0.84; v_{basin}: 0.99

440

v_{median}: 4; v_{mean}: 3.36; v_{std}: 1.43; rV_{99}: 2.8%
u: 0.42; v_{patch}: 1.00; v_{basin}: 1.00

23

v_{median}: 4; v_{mean}: 3.34; v_{std}: 1.24; rV_{99}: 7.8%
u: 0.46; v_{patch}: 0.46; v_{basin}: 0.46

3008

v_{median}: 4; v_{mean}: 3.32; v_{std}: 1.21; rV_{99}: 4.3%
u: 0.36; v_{patch}: 0.93; v_{basin}: 0.93

With few exceptions the images can predominantly be grouped into two categories. The first group look onto a valley side slope (typically [1792, 366, 1927, 2153]), while the second group has a perspective more along the valley axis (e.g. [4286, 642, 323, 3428]). There are few mixed cases.

Interesting is amongst others [366], where the impression of the image is rather that of looking down. There are also parts of a topographic depression visible, which lay lower than the observer point. Consequently, with a value of 3.7 the v_{mean} is also considerably lower than that of previous examples.

[2984] is interesting because the image itself does not inform the onlooker very well about the situation. Participants could only realise that the view is tilted upward and that a large landmass at a much higher altitude is visible. The foreground of the picture remains unclear, as well as what is behind the observer. However, (due to the mere height of the landmass in the picture) experience may convince a participant that it is unlikely that the depression the observer may be standing in may have a ground that is considerably lower than the observer point.

[1927] seems to be a comparably shallow depression. However, there is the special element of cables of a cable car. The fact that the cables are very close to the ground in the foreground of the image may inform the user that the observer point is in fact close to the valley station of a cable car.

[3428] is interesting because it shows that a prototypically shaped (long, v-shaped cross-section) topographic depression is seen as such, despite it being in the high mountains and snow-covered.

[1589] and [2026] seem similar. Especially [2026] does seem susceptible to be perceived as a plain, though. However, both images were ranked relatively valley-like. As opposed to [2026], in [1589] there is no indication of relatively nearby large mountains; there are only minor surface undulations visible next to the river. However, in both cases the rivers can act as an indicator that the presented scene is indeed a low place and elongate.

Finally, [440] is remarkable, since most similar stimuli experienced a large amount of variance in participants' answers (cf. subsequent sections).

Summarising, it seems that observer points which are obviously low, feature higher neighbouring grounds and often obviously level or flat make good candidates for being judged valley-like. On the other hand, places from which a both sides of a distinct, V-shaped part of the horizon can be seen and which lay relatively low in that horizon, seem to occur in the very valley-like group as well.

Stimuli with lowest valleyness. The next group of photographs represents stimulus images with v_{median} = 1 where the images are sorted according to v_{mean} in ascending order. Predominantly, the images have a level or – more seldom – a downward-looking perspective. Many of the pictures lead to the conclusion that the observer point is at equal (e.g. [4038, 1076, 1871, 2231, 85]) or even higher (e.g. [4321, 907, 927, 7, 1127]) height than the highest points in the view. Interestingly, most of the ten stimuli with lowest valleyness show snowy sceneries. However, in section 6.4.4 snow was shown to have no significant effect on v_{mean} and v_{median}.

4038
v_{median}: 1; v_{mean}: 1.11; v_{std}: 0.50; rV_{99}: 2.3%
u: 0.01; v_{patch}: 0.01; v_{basin}: 0.01

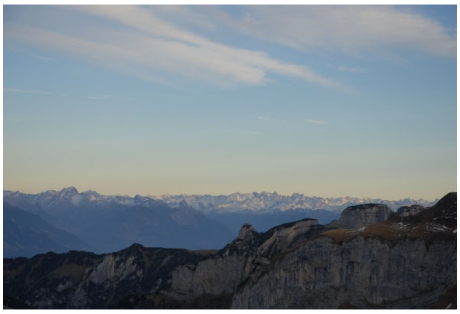
1076
v_{median}: 1; v_{mean}: 1.12; v_{std}: 0.61; rV_{99}: 1.4%
u: 0.03; v_{patch}: 0.03; v_{basin}: 0.03

4321
v_{median}: 1; v_{mean}: 1.14; v_{std}: 0.62; rV_{99}: 0.0%
u: 0.00; v_{patch}: 0.01; v_{basin}: 0.01

907
v_{median}: 1; v_{mean}: 1.15; v_{std}: 0.64; rV_{99}: 5.3%
u: 0.14; v_{patch}: 0.00; v_{basin}: 0.00

1871
v_{median}: 1; v_{mean}: 1.19; v_{std}: 0.68; rV_{99}: 0.9%
u: 0.05; v_{patch}: 0.20; v_{basin}: 0.30

2231
v_{median}: 1; v_{mean}: 1.32; v_{std}: 0.76; rV_{99}: 0.9%
u: 0.08; v_{patch}: 0.25; v_{basin}: 0.24



927

v_{median}: 1; v_{mean}: 1.39; v_{std}: 0.77; rV_{99}: 3.2%
u: 0.15; v_{patch}: 0.29; v_{basin}: 0.29

85

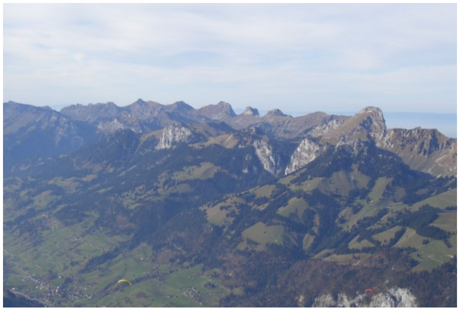
v_{median}: 1; v_{mean}: 1.43; v_{std}: 1.02; rV_{99}: 0.0%
u: 0.17; v_{patch}: 0.20; v_{basin}: 0.19

44

v_{median}: 1; v_{mean}: 1.49; v_{std}: 0.90; rV_{99}: 2.3%
u: 0.18; v_{patch}: 0.41; v_{basin}: 0.39

4448

v_{median}: 1; v_{mean}: 1.51; v_{std}: 0.88; rV_{99}: 1.0%
u: 0.14; v_{patch}: 0.06; v_{basin}: 0.06



2298

v_{median}: 1; v_{mean}: 1.52; v_{std}: 1.12; rV_{99}: 2.3%
u: 0.27; v_{patch}: 0.16; v_{basin}: 0.15

7

v_{median}: 1; v_{mean}: 1.55; v_{std}: 0.94; rV_{99}: 1.4%
u: 0.17; v_{patch}: 0.33; v_{basin}: 0.33

2264

v_{median}: 1; v_{mean}: 1.61; v_{std}: 1.02; rV_{99}: 1.9%
u: 0.22; v_{patch}: 0.07; v_{basin}: 0.07

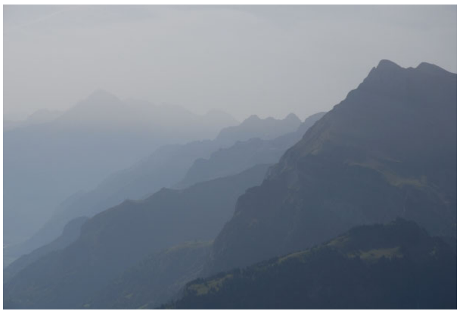
1457

v_{median}: 1; v_{mean}: 1.61; v_{std}: 1.03; rV_{99}: 1.1%
u: 0.20; v_{patch}: 0.16; v_{basin}: 0.12

1172
v_{median}: 1; v_{mean}: 1.63; v_{std}: 0.85; rV_{99}: 2.3%
u: 0.15; v_{patch}: 0.01; v_{basin}: 0.01

159
v_{median}: 1; v_{mean}: 1.64; v_{std}: 0.90; rV_{99}: 1.8%
u: 0.17; v_{patch}: 0.08; v_{basin}: 0.06

1978
v_{median}: 1; v_{mean}: 1.76; v_{std}: 1.00; rV_{99}: 0.9%
u: 0.18; v_{patch}: 0.64; v_{basin}: 0.62



684
v_{median}: 1; v_{mean}: 1.80; v_{std}: 1.07; rV_{99}: 6.0%
u: 0.34; v_{patch}: 0.06; v_{basin}: 0.06

4654
v_{median}: 1; v_{mean}: 1.80; v_{std}: 1.28; rV_{99}: 3.2%
u: 0.36; v_{patch}: 0.21; v_{basin}: 0.25

3702
v_{median}: 1; v_{mean}: 1.82; v_{std}: 1.17; rV_{99}: 5.5%
u: 0.37; v_{patch}: 0.19; v_{basin}: 0.18

2811
v_{median}: 1; v_{mean}: 1.87; v_{std}: 1.26; rV_{99}: 0.0%
u: 0.27; v_{patch}: 0.20; v_{basin}: 0.20

1869
v_{median}: 1; v_{mean}: 1.93; v_{std}: 1.15; rV_{99}: 12.2%
u: 0.54; v_{patch}: 0.15; v_{basin}: 0.15

421
v_{median}: 1; v_{mean}: 1.97; v_{std}: 1.23; rV_{99}: 4.1%
u: 0.37; v_{patch}: 0.06; v_{basin}: 0.06

2159
v_{median}: 1; v_{mean}: 2.04; v_{std}: 1.39; rV_{99}: 1.4%
u: 0.36; v_{patch}: 0.20; v_{basin}: 0.20

4954
v_{median}: 1; v_{mean}: 2.07; v_{std}: 1.33; rV_{99}: 5.9%
u: 0.45; v_{patch}: 0.88; v_{basin}: 0.86

1681
v_{median}: 1; v_{mean}: 2.21; v_{std}: 1.54; rV_{99}: 8.8%
u: 0.62; v_{patch}: 1.00; v_{basin}: 1.00

Interesting is amongst others [7], where the view goes onto a relatively flat landscape which is markedly lower than the observer. The same holds to a slightly lesser degree for [159], while for [159] it could be argued that participants may perceive a valley in the centre of the image. More clearly there are valleys in the view of the observer in [1978, 684, 2811, 2159, 4954]. However, probably the observer point was judged to be located too high in comparison to the feature to be still judged valley-like. In [1869] there may be a confounding effect. While the view is onto a feature which is decidedly not valley-like, the fact that the view is directed upward may hint that the observer is indeed standing in a valley-like area. However, participants still predominantly judged the position not valley-like; but they also showed a significant amount of uncertainty with a value of 12.2% for rV_{99}. [1681] is remarkable because it resembles [1589] from the group of stimuli with high valleyness. Probably [1681] too clearly hinted at the location being in a very wide, very flat (both absence of horizon) and low place (large river, settlement).

The sometimes not very low values for combined valleyness v stem in most cases from the elevation-based component v_e. Of the stimuli with a considerable valleyness (> 0.15) only [85, 1869, 1978, 3702, 4654] had a convexity-based valleyness v_c which was higher than v_e.

Stimuli with lowest spread regarding valleyness. The next group of photographs represents stimulus images with $v_{std} \leq 1$. Many of the photographs have been featured in previous sections about the stimuli with highest or lowest valleyness. The stimuli which newly appear listed are marked with an asterisk (*). The overwhelming majority of images have a median valleyness value, v_{median}, of 1. All but two images have a $v_{median} \leq 2$. Of all images listed only [4963, 1792] are considered to be photographed from valley-like locations.

This shows clearly, that participants can much more easily agree on places which are not valley-like than on places which are valley-like. Potentially, in a larger context, this can be a hint that it is much easier to agree on what is not a valley than on what is a valley – or even more generally, that topographic eminences such as mountains are more clearly defined features than topographic depressions such as valleys (see also e-mail 4 in Appendix G on this point).

4038
v_{median}: 1; v_{mean}: 1.11
v_{std}: 0.50; rV_{99}: 2.3%
v_{patch}: 0.01; v_{basin}: 0.01

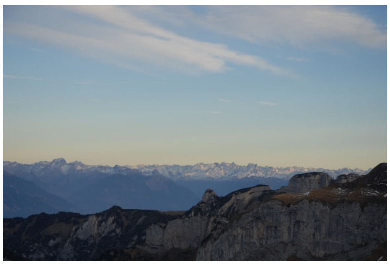
1076
v_{median}: 1; v_{mean}: 1.12
v_{std}: 0.61; rV_{99}: 1.4%
v_{patch}: 0.03; v_{basin}: 0.03

4321
v_{median}: 1; v_{mean}: 1.14
v_{std}: 0.62; rV_{99}: 0.0%
v_{patch}: 0.01; v_{basin}: 0.01

907
v_{median}: 1; v_{mean}: 1.15
v_{std}: 0.64; rV_{99}: 5.3%
v_{patch}: 0.00; v_{basin}: 0.00

1871
v_{median}: 1; v_{mean}: 1.19
v_{std}: 0.68; rV_{99}: 0.9%
v_{patch}: 0.20; v_{basin}: 0.30

2231
v_{median}: 1; v_{mean}: 1.32
v_{std}: 0.76; rV_{99}: 0.9%
v_{patch}: 0.25; v_{basin}: 0.24



927
v_{median}: 1; v_{mean}: 1.39
v_{std}: 0.77; rV_{99}: 3.2%
v_{patch}: 0.30; v_{basin}: 0.30

4963
v_{median}: 5; v_{mean}: 4.52
v_{std}: 0.79; rV_{99}: 0.5%
v_{patch}: 0.91; v_{basin}: 0.91

1172
v_{median}: 1; v_{mean}: 1.63
v_{std}: 0.85; rV_{99}: 2.3%
v_{patch}: 0.01; v_{basin}: 0.01

4448
v_{median}: 1; v_{mean}: 1.51
v_{std}: 0.88; rV_{99}: 1.0%
v_{patch}: 0.06; v_{basin}: 0.06

159
v_{median}: 1; v_{mean}: 1.64
v_{std}: 0.90; rV_{99}: 1.8%
v_{patch}: 0.08; v_{basin}: 0.06

44
v_{median}: 1; v_{mean}: 1.49
v_{std}: 0.90; rV_{99}: 2.3%
v_{patch}: 0.41; v_{basin}: 0.39

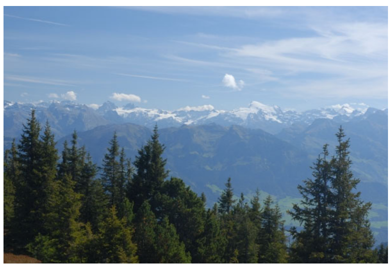
7
v_{median}: 1; v_{mean}: 1.55
v_{std}: 0.94; rV_{99}: 1.4%
v_{patch}: 0.33; v_{basin}: 0.33

1715 *
v_{median}: 2; v_{mean}:1.88
v_{std}: 0.94; rV_{99}: 5.1%
v_{patch}: 1.00; v_{basin}: 1.00

1649 *
v_{median}: 2; v_{mean}: 1.73
v_{std}: 0.94; rV_{99}: 1.6%
v_{patch}: 0.23; v_{basin}: 0.23

1792
v_{median}: 4; v_{mean}: 4.17
v_{std}: 0.96; rV_{99}: 2.3%
v_{patch}: 0.53; v_{basin}: 0.53

1657 *
v_{median}: 2; v_{mean}: 1.85
v_{std}: 0.96; rV_{99}: 3.6%
v_{patch}: 0.17; v_{basin}: 0.17



243 *
v_{median}: 2; v_{mean}: 1.83
v_{std}: 0.97; rV_{99}: 3.7%
v_{patch}: 0.12; v_{basin}: 0.12

1978
v_{median}: 1; v_{mean}: 1.76
v_{std}: 1.00; rV_{99}: 0.9%
v_{patch}: 0.64; v_{basin}: 0.62

Stimuli with highest spread regarding valleyness. The next group of photographs represents stimulus images with $v_{std} \geq 1.5$. All but those flagged with an asterisk (*) were considered suspected plains when the author of this thesis attributed all stimuli with indicator variables (importantly, this was *before* and *independent of* the compilation of the following set of pictures).

The set of stimuli with highest spread regarding valleyness predominantly encompasses pictures of low and rather flat places. Many of the pictures feature water in a substantial proportion of the image area. These images fell within the class with the highest spread very probably because of the afore-mentioned (4C.4.3) trichotomy *plain – valley – mountain* (rather than *valley vs. non-valley* or *valley vs. mountain*). Some people considered the observer location to be very valley-like, while others had a contrary perception.

[4961] is special in so far as it shows (with little controversy) a valley floor from above. Here the split in the answers given by participants could be due to uncertainty with regard to the extent of the valley (‘is the observer located on the valley edge/ridge bounding the valley or is she positioned mid-slope?’) and/or due to the inexact assumption of the task (e.g. some people correctly characterised the observer location, while other people were incorrectly drawn towards characterising the image content). With [1447] probably the same reasoning implies with maybe a slight favour of the former argument.

654
v_{median}: 3; v_{mean}: 2.89; u: 0.55
v_{std}: 1.64; rV_{99}: 4.3%
v_{patch}: 1.00; v_{basin}: 1.00

5268
v_{median}: 2; v_{mean}: 2.64; u: 0.60
v_{std}: 1.59; rV_{99}: 7.4%
v_{patch}: 1.00; v_{basin}: 1.00

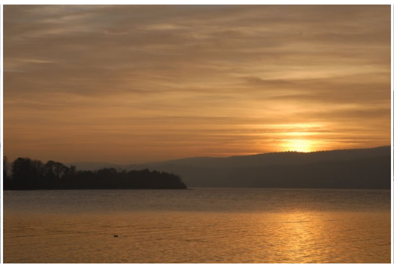
4961 *
v_{median}: 2; v_{mean}: 2.49; u: 0.47
v_{std}: 1.58; rV_{99}: 2.6%
v_{patch}: 0.72; v_{basin}: 0.90

4964
v_{median}: 2; v_{mean}: 2.60; u: 0.73
v_{std}: 1.54; rV_{99}: 13.3%
v_{patch}: 0.95; v_{basin}: 0.95

1681
v_{median}: 1; v_{mean}: 2.21; u: 0.62
v_{std}: 1.54; rV_{99}: 8.8%
v_{patch}: 1.00; v_{basin}: 1.00

5357
v_{median}: 2; v_{mean}: 2.70; u: 0.57
v_{std}: 1.54; rV_{99}: 7.3%
v_{patch}: 1.00; v_{basin}: 1.00

444
v_{median}: 2; v_{mean}: 2.40; u: 0.55
v_{std}: 1.53; rV_{99}: 6.2%
v_{patch}: 1.00; v_{basin}: 1.00



1308
v_{median}: 2; v_{mean}: 2.35; u: 0.54
v_{std}: 1.52; rV_{99}: 6.2%
v_{patch}: 1.00; v_{basin}: 1.00

448
v_{median}: 2; v_{mean}: 2.65; u: 0.48
v_{std}: 1.51; rV_{99}: 3.8%
v_{patch}: 0.97; v_{basin}: 0.98

1447 *
v_{median}: 3; v_{mean}: 3.14; u: 0.39
v_{std}: 1.50; rV_{99}: 0.5%
v_{patch}: 0.69; v_{basin}: 0.76

446
v_{median}: 3; v_{mean}: 2.88; u: 0.49
v_{std}: 1.50; rV_{99}: 4.7%
v_{patch}: 1.00; v_{basin}: 1.00

4977
v_{median}: 3; v_{mean}: 2.99; u: 0.55
v_{std}: 1.50; rV_{99}: 6.9%
v_{patch}: 0.99; v_{basin}: 1.00

Stimuli with most "non-answers". The standard deviation of valleyness estimates, v_{std}, and the proportion of participants not being able to answer (the amount of "non-answers"), rV_{99}, are statistically significantly correlated ($p < 0.001$) but not very strongly so (Spearman's rho of 0.347). In fact quite some of the stimuli with high spreads of valleyness shown above have quite low values of rV_{99}. Thus it is sensible to treat the dimension of rV_{99} separately. All of the following stimuli have values of $rV_{99} > 10\%$.

2510
v_{median}: 3; v_{mean}: 2.95; u: 1.00
v_{std}: 1.31; rV_{99}: 28.0%
v_{patch}: 0.44; v_{basin}: 0.42

5179
v_{median}: 2; v_{mean}: 2.59; u: 0.69
v_{std}: 1.24; rV_{99}: 17.0%
v_{patch}: 0.27; v_{basin}: 0.26

4164
v_{median}: 2; v_{mean}: 2.42; u: 0.67
v_{std}: 1.18; rV_{99}: 17.0%
v_{patch}: 0.48; v_{basin}: 0.48

1289
v_{median}: 3; v_{mean}: 2.75; u: 0.55
v_{std}: 1.06; rV_{99}: 14.2%
v_{patch}: 1.00; v_{basin}: 1.00

5155
v_{median}: 2; v_{mean}: 2.27; u: 0.68
v_{std}: 1.39; rV_{99}: 13.8%
v_{patch}: 0.10; v_{basin}: 0.10

2847
v_{median}: 3; v_{mean}: 3.10; u: 0.59
v_{std}: 1.17; rV_{99}: 13.8%
v_{patch}: 1.00; v_{basin}: 0.97

4964
v_{median}: 2; v_{mean}: 2.60; u: 0.73
v_{std}: 1.54; rV_{99}: 13.3%
v_{patch}: 0.95; v_{basin}: 0.95

1869
v_{median}: 1; v_{mean}: 1.93; u: 0.54
v_{std}: 1.15; rV_{99}: 12.2%
v_{patch}: 0.15; v_{basin}: 0.15

1784
v_{median}: 2; v_{mean}: 2.33; u: 0.52
v_{std}: 1.16; rV_{99}: 11.4%
v_{patch}: 0.53; v_{basin}: 0.52

350
v_{median}: 3; v_{mean}: 2.78; u: 0.52
v_{std}: 1.18; rV_{99}: 11.2%
v_{patch}: 0.28; v_{basin}: 0.28

862
v_{median}: 2; v_{mean}: 2.40; u: 0.48
v_{std}: 1.13; rV_{99}: 10.6%
v_{patch}: 1.00; v_{basin}: 0.92

1251
v_{median}: 2; v_{mean}: 2.56; u: 0.46
v_{std}: 1.09; rV_{99}: 10.4%
v_{patch}: 0.27; v_{basin}: 0.26

5263
v_{median}: 3; v_{mean}: 2.82; u: 0.55
v_{std}: 1.31; rV_{99}: 10.4%
v_{patch}: 0.47; v_{basin}: 0.47

This set of stimuli is considerably less homogeneous with regard to the images' characteristics than all of above groups. Probably the most common property is the lack of a 'wider perspective'. In images such as [2510, 5179, 5155, 1784, 350] (and a bit less so in e.g. [4164, 1289, 2847, 862]) it is hard to judge the location of the observer because (very) little of the surrounding area is visible; be it through the choice of direction and extent of the photograph or through potential obstruction by, for instance, trees or fog.

Stimuli with fewest "non-answers". All images in the following group of stimuli have values of $rV_{99} < 1\%$ (besides, only the first three image below have $rV_{99} = 0\%$). This set of stimuli is again more homogeneous with regard to the images' characteristics. Many of the images ([2811, 85, 4321, 1978, 2231, 1871]) are of the group with lowest valleyness values. [4286, 4963, 3428] are amongst the images with the highest valleyness values. This is not very surprising, since one would expect that if participants have a strong, extreme opinion (*very valley-like* or *very un-valley-like*) one would expect that there are less people who feel they cannot make a judgment of the valleyness.

Out of the three remaining images [5442] is interesting since according to v_{mean}, it almost takes the middle position in the range of valleyness. Intuitively, [1447] and [1010] (a bit less maybe [5442]) should actually induce relatively little uncertainty in the questionnaire participants, since they at least clearly show a valley. However, these images leave the uncertainty regarding the observer location with regard to the valley in the picture, of course.

2811
v_{median}: 1; v_{mean}: 1.87; u: 0.27
v_{std}: 1.26; rV_{99}: 0.0%
v_{patch}: 0.20; v_{basin}: 0.20

85
v_{median}: 1; v_{mean}: 1.43; u: 0.17
v_{std}: 1.02; rV_{99}: 0.0%
v_{patch}: 0.20; v_{basin}: 0.19

4321
v_{median}: 1; v_{mean}: 1.14; u: 0.00
v_{std}: 0.62; rV_{99}: 0.0%
v_{patch}: 0.01; v_{basin}: 0.01

4286
v_{median}: 4; v_{mean}: 4.14; u: 0.20
v_{std}: 1.05; rV_{99}: 0.5%
v_{patch}: 1.00; v_{basin}: 0.97

4963
v_{median}: 5; v_{mean}: 4.52; u: 0.08
v_{std}: 0.79; rV_{99}: 0.5%
v_{patch}: 0.91; v_{basin}: 0.91

3428
v_{median}: 4; v_{mean}: 3.42; u: 0.30
v_{std}: 1.29; rV_{99}: 0.5%
v_{patch}: 0.88; v_{basin}: 0.83

5442
v_{median}: 2; v_{mean}: 2.37; u: 0.29
v_{std}: 1.54; rV_{99}: 7.3%
v_{patch}: 0.29; v_{basin}: 0.29

1447
v_{median}: 3; v_{mean}: 3.14; u: 0.39
v_{std}: 1.50; rV_{99}: 0.5%
v_{patch}: 0.69; v_{basin}: 0.76

1010
v_{median}: 2; v_{mean}: 2.19; u: 0.30
v_{std}: 1.28; rV_{99}: 0.5%
v_{patch}: 0.72; v_{basin}: 0.72

1978
v_{median}: 1; v_{mean}: 1.76; u: 0.18
v_{std}: 1.00; rV_{99}: 0.9%
v_{patch}: 0.64; v_{basin}: 0.62

2231
v_{median}: 1; v_{mean}: 1.32; u: 0.08
v_{std}: 0.76; rV_{99}: 0.9%
v_{patch}: 0.25; v_{basin}: 0.24

1871
v_{median}: 1; v_{mean}: 1.19; u: 0.05
v_{std}: 0.68; rV_{99}: 0.9%
v_{patch}: 0.20; v_{basin}: 0.30

Appendix G: Feedback from questionnaire participants

Below are translations of (excerpts of) the feedback e-mails I have received from participants of the questionnaire survey. While some of them sound funny, this should not distract from the very valuable assertions in them, namely that the concept *valley* lacks a formal, generally known definition and that assessing the valleyness of a location of an image is indeed a difficult task!

E-mail 1:

> Hi Ralph,
>
> Partly, answering the questions was really quite tricky, since I don't even know exactly, how a "valley" is defined. Is a lake with mountains on the horizon in a valley or not??! :-)
>
> Cheers,
>
> J. H.

E-mail 2:

> Hi Ralph!
>
> Have you tested this questionnaire with non-geographers before?
>
> What does "Definitely not in a valley." mean, if one is located on a mountain slope? Where, for the LOCATION of the observer does "I am in the valley!" start? Where does it end? Where does one say: "I am on the mountain!"?
>
> This was absolutely unclear and I hope, you don't have to have the questionnaire filled in one more time…. (Although, I'd probably do it, for the sake of science.)
>
> I mean: Given I see a valley that does not have to mean, that I am in the valley. I can be located on the slope, or on the summit, or on a lake…. From which width (in relation) is a lake located not in a valley anymore, but is simply a lake in a plain? Questions over questions.
>
> Kind regards,
>
> T. H.

Both these e-mail authors point out the problem of the pictures containing lakes and/or what many persons may deem a plain rather than a valley. This effect was discussed in Section 6.4.4 and dealt with in Section 6.4.5.

E-mail 3:

> Hello
>
> I have filled in your questionnaire regarding valleyness. Now I'd like to give you some feedback. (I am not offended, if this mail is trashed unread.)
>
> I found it nigh impossible for almost all photographs, to define the valleyness, since one has to figure out oneself, how the immediate neighbourhood of the photographer looks like. Besides, during the whole exercise I kept asking myself if I really have to assess the location of the photographer and not the depicted landscape.
>
> Best regards,
>
> A. B.

This person once more highlights, that the task which was posed to the participants was indeed a difficult one. Hopefully, most participants heeded the advice to estimate the valleyness of the photographer's location which, for that reason, was repeated beneath every stimulus image and above every Likert scale where participants entered their answers.

E-mail 4:

> Well, Ralph – I have just filled in your questionnaire and I find it a difficult thing with this "valleyness". Especially in those cases, where in my opinion the photographer is located somewhere on a slope.
> What then is "valley" and what is "mountain?": In my perception two unequally crisply defined terms: There, "valley" is much more fuzzy than "mountain" – at least, I had this distinct impression looking at the images. Thus, I now simply allege that in doubt "valley" is the preferred choice over "mountain". This as a feedback.
> Cheers,
> B. S.

Finally, the last person to give feedback nicely highlights some of the questions my mind indeed has kept reeling about during the writing of this thesis. They are tied to the conceptual and spatial vagueness of landform terms and are justly asked.

However, I would argue that the terms *valley* and *mountain* are easily and often used by most of the people who gave feedback (and basically, everybody else). That in the questionnaire participants were asked to assess valleyness probably rendered them (overly) conscious about and thus critical of the involved process of 'fiat parsing the elevation field' (Smith and Mark 2003).

Credit where credit is due: The question whether people 'when in doubt' do favour assessing a photographer location as valley-like, inspired me to a brief investigation into this matter (as far as this was possible with the available data); this is contained in Section 6.4.6 of this thesis.

Curriculum vitae

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- Straumann R. K. and Purves R. S. (submitted): Computation and elicitation of valleyness. Spatial Cognition and Computation.
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- Straumann R. K. (2009): Experiences in developing landform ontologies (extended abstract). Purves R. S., Gruber S., Hengl T. and Straumann R. K. (eds.): Proceedings of Geomorphometry 2009, 17–21.
- Purves R. S., Gruber S., Hengl T. and Straumann R. K. (eds., 2009): Proceedings of Geomorphometry 2009, 31 August – 2 September 2009, Zurich, Switzerland.
- Straumann R. K. and Korup O. (2009): Quantifying postglacial sediment storage at the mountain-belt scale (abstract). Geophysical Research Abstracts, 11, 2009 EGU General Assembly. (not peer-reviewed)
- Straumann R. K. and Purves R. S. (2008): Delineation of valleys and valley floors. Lecture Notes in Computer Science, 5266. Cova T. J., Miller H. J., Beard K., Frank A. U. and Goodchild M. F. (eds.): Geographic Information Science, Proceedings of GIScience 2008, 320–336.
- Straumann R. K. and Purves R. S. (2007): Resolution sensitivity of a compound terrain derivative as computed from LiDAR-based elevation data. Lecture Notes in Geoinformation & Cartography. Fabrikant S. I. and Wachowicz M. (eds.): The European Information Society – Leading the Way with Geo-Information, Proceedings of AGILE 2007, 87–109.
- Straumann R. K. (2006): Sensitivität von Prozessmodellen in Bezug auf die Auflösung LIDAR-basierter Höhendaten. Diploma thesis, Department of Geography, University of Zurich, Switzerland.