# Delineation of Valleys and Valley Floors

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**Abstract.** Methods to automatically derive landforms have typically focused on pixel-based, bottom-up approaches and most commonly on the derivation of topographic eminences. In this paper we describe an object-based, top-down algorithm to identify valley floors. The algorithm is based on a region growing approach, seeded by thalwegs with pixels added to the region according to a threshold gradient value. Since such landforms are *fiat* we compare the results of our algorithm for a particular valley with a number of textual sources describing that valley. In a further comparison, we computed a pixel-based six-fold morphometric classification for regions we classified as either being, or not being, valley floor. The regions classified as valley floor are dominated by planar slopes and channels, though the algorithm is robust enough to allow local convexities to be classified as within the valley floor. Future work will explore the delineation of valley sides, and thus complete valleys.

**Keywords:** Landform, geomorphometry, valley, valley floor, delineation.

## 1 Introduction

Since the early 1990s the explosion of availability of spatial data in general, and data describing the elevation of the earth's surface in particular, has led to considerable effort by geomorphologists and GIScientists to develop techniques capable of describing and delineating the features which go together to make up a landscape. In many ways, such research is a return to early ideas expressed by Maxwell [1] in his treatise "On hills and dales". In this paper, we are particularly interested in the delineation of landforms, that is to say attempts to answer questions such as "*Where* is a mountain?" posed by Fisher et al. [2]. However, in our exploration of the literature we noted a concentration by GIScientists on the delineation of mountains (e.g. ibid., [3]) or, as they are also more neutrally termed, *topographic eminences* [4]. Further, Hugget [5], a geomorphologist, states that "valleys are so common that geomorphologists seldom defined them and, strangely, tended to overlook them as landforms". Thus, in this paper we describe research which aims to explore a range of techniques for the extraction of valleys, concentrating on *valley floors*. Importantly, we are concerned not with the extraction of channel networks (the *thalweg*), but with deriving the spatial extent associated with a valley floor.

An important prerequisite to extracting landforms is to consider what the term itself implies. In the literature there appear to be two contrasting, and for GIScientists

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familiar, sets of definitions. The first set of definitions are essentially field-based. For example, Whittow [6] defines landform as "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". Following this definition, landforms are defined by fields of continuous attributes (e.g. gradient and curvature) and a multitude of what we will term pixel-based extraction techniques have been developed which set out to extract landform elements on the basis of similarities in these attributes. The second set of definitions view landforms as objects, with for example Lapidus et al. [7] and Blasczczinski [8] giving examples of landforms which include mountains, valleys, rivers and canyons.

These two sets of definitions lead, in turn, to two different approaches to the problem of extracting landform(s) (elements). In the case of a field-based view of landforms, the problem is essentially bottom-up. Attributes are defined over an entire landscape, and a range of techniques applied to identify areas within a landscape with similar attribute values. By inspection of attribute values within similar landform elements, they may be assigned either a name reflecting simply these attribute values (e.g. double-convex slopes), or be associated with a landform (e.g. convex local maxima may be assigned to the landform topographic eminence). In an object view of landforms the essential difference is that the starting point is some notion of the landform under investigation, which in turn leads to a top-down method. Thus, our starting point is to characterise a landform of interest (e.g. a valley) before applying a range of methods to delineate the boundaries or, if we adopt a fuzzy approach similar to that proposed by Fisher et al. [2], the *valleyness* of locations.

In this paper we describe a case study with a special focus on Gürbe valley in Switzerland, using techniques based on both popular notions of Gürbe valley and a top-down method developed to extract valley floors from DEMs. We firstly set out a range of related work on the extraction and definition of landforms and landform elements, as well as the application of Naïve Geography to delineating object boundaries and list a series of definitions of the landforms valley and valley floor. We then describe simple methods to extract Gürbe valley from natural language descriptions, before we introduce a DEM-based algorithm for the delineation of valley floors. The algorithm results are illustrated over Switzerland as a whole before we describe them in detail for the Gürbe valley and relate them to the natural language descriptions and compare our results with a pixel-based classification.

## 2 Related Work

### 2.1 Describing Landscapes in Terms of Surface Form

Geomorphometry can be defined as the quantitative measurement and analysis of the form of the earth's surface. A range of attributes are used in describing this form (cf. e.g. [9, 10]). In GIScience terms these attributes can be split into focal, zonal and global measures. Basic focal attributes encompass the first order derivatives of elevation, i.e. slope in terms of magnitude (gradient) and direction (aspect) [11, 12]. Profile, plan and a variety of additional curvature measures (cf. [13]) are second order derivatives of elevation. All these measures can be approximated from a moving window through a focal operation, typically with a neighbourhood of 3x3 cells, though Wood [14] and others have emphasised the importance of scale (and thus varying window size) on the derivation of such attributes.

Zonal attributes are computed within some defined analysis region. Local relief [15] defined as the range of elevations in an area is an example. The hypsometric curve and the hypsometric integral are also calculated over a pre-defined region, typically a drainage basin.

Global attributes, which in principle can consider any cell within the study area, are typically more complex to compute. Examples are the distance to a local depression, the elevation above local depression [16] or ridge proximity [17].

Compound derivatives combine two or more terrain attributes which may be focally, zonally or globally defined. Examples in geomorphology include the topographic wetness index [18, 19] and the stream power index [10].

**Pixel-Based Bottom-Up Approaches.** Pixel-based bottom-up approaches are numerous. They can be roughly subdivided into supervised (classification) and unsupervised (clustering; classical bottom-up) approaches. The latter first choose attributes on which the clustering process is to take place, before forming either crisp or fuzzy clusters by minimising intra-class variance and maximising inter-class variance (e.g. [20, 17, 21]).

Supervised classification utilises either training data or values from the literature to identify clusters within data. Pennock et al. [22] proposed a seven-fold crisp classification based on Ruhe's [23] profile form classes. A similar scheme was put forward by Dikau [24] and modified by Wood [14]. These classification schemes have – sometimes in adapted or extended form – often been applied to derive both crisp [25, 26, 27, 28] and fuzzy [29, 30] classifications. Wood [14] proposed multi-scale classification which was extended into fuzzy multi-scale classification based on a range of crisp classifications at different scales [2].

**Object-Based Top-Down Approaches.** Besides pixel-based approaches characterisations of topography can result in defined objects, rather than classified pixels (clearly, pixel-based characterisations can be used to derive objects by the identification of some threshold value). For example, Lucieer and Stein [31] use a texture measure, as well as other attributes, to seed a region growing algorithm. However, no *a priori* knowledge about landforms is utilised, making the process essentially data-driven.

Fisher et al. [2] present a partially top-down approach where they reason about the essence of peaks and their relationship to summits. They use fuzzy multi-scale classification into six morphometric classes resulting in fuzzy areas of peakness associated with summits. Although the result is a raster representation of fuzzy regions, the applied parameters allow individual peaks to be separated from each other. Recently, a number of methods have been developed which both incorporate *a priori* knowledge and are object-based [3, 32]. Their methods use peak contributing areas and prominence to delineate mountains and hills and ranges.

## 2.2 Determining Region Boundaries

In identifying the borders of any region, or to be more specific in our case, landform, it is important to consider the nature of the region and its borders. Landforms are generally classical examples of *fiat* objects – that is to say they are defined by human perception and do not have a physically unambiguous expression on the earth's surface because they are vague [33]. Thus, regarding our case study, the area which is unambiguously Gürbe valley cannot, by definition, be defined. Recent work has sought to define the boundaries of similar 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. [34] investigated this problem by asking residents of Santa Barbara to sketch the boundaries of downtown on a map. More recently, Jones et al. [35] 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.

### 2.3 Defining Valleys

There is a range of definitions for the term "valley" in the literature. Here we give three typical examples:

1. a low area more or less enclosed by hills [36];
2. a long, narrow depression in the Earth's surface, usually with a fairly regular downslope (Spatial Data Transfer Standard; [37, 38]); 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 [39].

As opposed to the extremely general 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.
According to the above definitions, characteristics of valleys include the following:

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

The terms 'valley floor' or 'valley bottom' appear infrequently in the literature. However, the Dictionary of Earth Science [40] 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 [39] define it as "the comparatively broad, flat bottom of a valley; (...)" and refer to "valley bottom" and "flood plain" as synonyms. However, 'flood plain' has the implication/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 listed above.

## 2.4 Delineating Valleys

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

Tribe [41] 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. In a follow-up paper, Tribe [42] 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 [43] is 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 [44] 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" [44: 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 [45] which aimed at further describing the extracted mountain-objects with additional topographic attributes (cf. also [46]).

Chorowicz et al. [47] 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. [48] studied the extraction of what they term ridge and valley connectivity networks (RCN and VCN). The authors use multi-scale opening and closing, as well as 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 [49]. 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 described, curvature-based methods have been implemented by several authors (e.g. [14, 2]) on a multi-scale basis – operationalised as varying window sizes for curvature calculation. However, the latter study focused on mountains or convexities rather than valleys. While these multi-scale methods account for the fuzziness of landforms they generate pixel-based characterisations ('channelness') rather than contiguous objects such as valleys or valley floors. Also, while the multi-scale nature of the 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 applied a similar method, but based on the application of slope (representing flatness) and elevation percentiles (representing lowness with respect to surroundings), to the classification of valley bottoms [50].

### 2.5 Research Gaps

In general, work on the delineation of landforms and landform elements has focused on bottom-up methods, often pixel-based, and especially the delineation of topographic eminences. In this paper, we therefore wish to address the issue of the extraction of valley (floors) from two perspectives – one based around Naïve Geography and the other focusing on a top-down geomorphometric approach. Furthermore, we wish to compare the results of the applied method to a pixel-based method, the classification into six geomorphometric classes identified by Wood [14].

## 3 Defining the Gürbe Valley through Naïve Geography

For Naïve Geography delineations of the Gürbe valley we looked primarily at natural language descriptions from internet sources provided by both the general public and a tourism organisation in the area. They 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 limitations, Wikipedia is used and referred to by the public. Wikipedia 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 7$^{th}$, 2008 [51].

For the tourism perspective we referred to the tourism association of the Gürbe valley (Verkehrsverband Region Gürbetal, [52]) which owns the internet domain 'www.guerbetal.ch'. We obtained a snapshot of the website as of February 2$^{nd}$, 2007 from the internet archive [53].

In order to gain additional clues on the extent of the Gürbe valley and some other topographic features mentioned e.g. by Wikipedia, we analysed toponyms used in Swiss topographic maps, similarly to [2]. For this purpose we used three scales of Swiss maps: 1:25,000, 1:50,000 and 1:100,000.

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, whilst region boundaries were used *as is*.

## 4 Automatically Extracting Valley Floors

### 4.1 Operationalisation

In developing a method for the extraction of valleys, the eventual aim of our work, Maxwell [1] was chosen as a starting point. The dales as defined by Maxwell equal drainage basins and effectively enclose valleys. While the enclosing relation may be one-to-one (typically in small headwater drainage basins), this is of course not necessarily the case for larger drainage basins which may contain several valleys. Thus, in order to narrow down the search area for valleys, which we consider to have a one-to-one relationship with valley floors, we clip drainage basins of a certain Shreve order with contributing drainage basins of lower orders (cf. also [54]). A drainage sub-basin is thus defined, a core area more closely related to one valley than the original drainage basin.

Starting from the definitions in section 2.3 we assumed that streams or thalwegs could well serve as conceptual cores of valleys and their floors. Valley floors can then 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 our assertions on the relations of drainage (sub-)basins and valleys we also imposed drainage sub-basin constraints – region growing only occurs within, and not across, sub-basins.

## 4.2 Implementation

The procedure of extracting approximations to valley floors is as follows. First, the SRTM DEM [55] was projected into the Swiss national projection system and resampled to 100 m resolution. The DEM was then filled and D8 flow directions and a flow accumulation grid calculated. By imposing a channel initiation threshold of $\geq 500$ cells a stream network and its Shreve ordering was derived, with pourpoints being created where stream of differing orders merged.

Subsequently, drainage basins of order x were clipped by all drainage basins of order $y < x$. The use of Shreve ordering led to a segmentation of the drainage basins in general flow direction, i.e. each segment of a river between two tributaries has its own drainage sub-basin, cf. Fig. 1. 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.

Using this raster and a raster of the streams a region growing procedure using stream cells as seeds was carried out. Growing was allowed to occur only within an

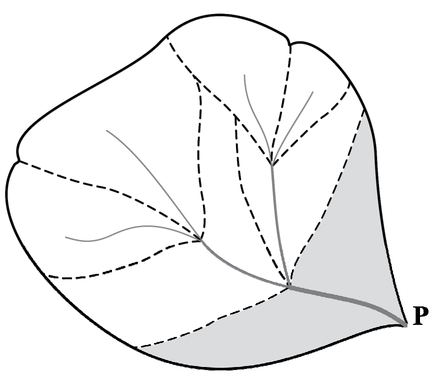


**Fig. 1.** Clipping of drainage basins. Solid outline represents original drainage basin of point P, dashed outlines represent several drainage sub-basins pertaining to different streams (grey lines). The drainage sub-basin of point P is represented by the grey area.

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 one of the following conditions concerning the elevations of cell *i* and the seed cell was met:

$$\text{Cardinal neighbours: } \tan(\gamma_{thrsh}) \cdot \lambda \geq elev_i - elev_{seed} \geq 0m . \quad (1)$$

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

where $\gamma_{thrsh}$: gradient threshold [°], $\lambda$: 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 section 2.3. Region growing was run iteratively until no new valley floor cells were detected. We tested a range of gradient thresholds ($\gamma_{thrsh}$) from 0.25° to 3° where, through qualitative visual examination, a threshold value of 1.5° gave the most promising results and was used in the following evaluation.

## 5 Results and Discussion

Fig. 2 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

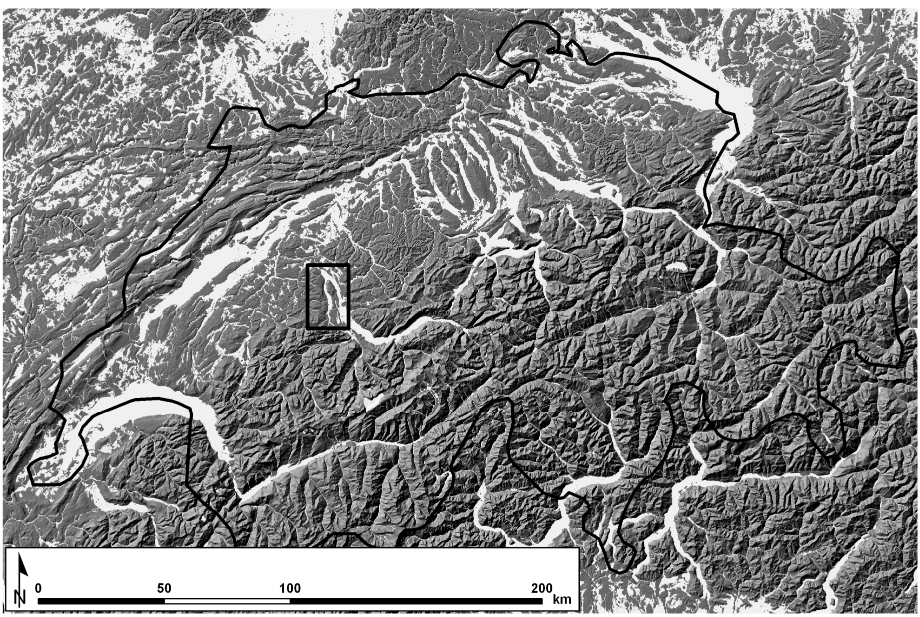


**Fig. 2.** Delineation of valley floors (light grey areas) using 1.5° threshold in the area of Switzerland (border in black). The black square denotes the region of the Gürbe (and Aar) valley subsequently analysed in detail.

Switzerland, Liechtenstein and Austria in the upper right corner and the Rhône valley in south-western 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.

In the remainder of this section we will compare the extent of the delineated valley floor in the Gürbe valley – a prealpine valley marked by the square in Fig. 2 – to valley delineations based on Naïve Geography descriptions of the area. Subsequently we compare our valley floor delineation to the distribution of six morphometric classes [14].

## 5.1 Comparison with Naïve Geography Delineations

The following excerpt is our translation of the entry in the German-speaking Wikipedia article "Gürbetal" (Gürbe valley) [56]:

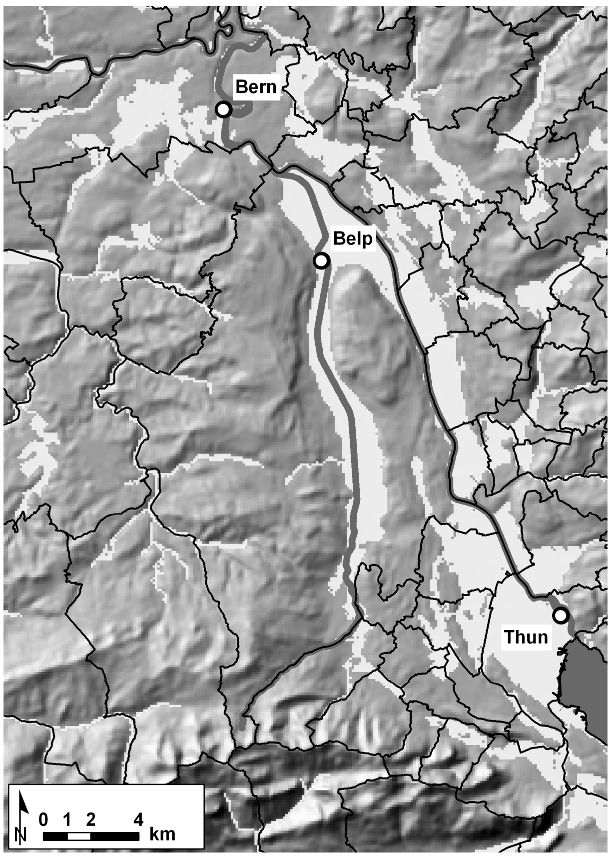


**Fig. 3.** Characterisation of the Gürbe valley in the German-speaking Wikipedia. Black linear features are administrative boundaries (large, in the middle: district of Seftigen; smaller: adjacent municipalities), dark grey features are water bodies. Background is a hillshaded DEM with delineated valley floors superimposed in light grey.

"The Gürbe valley is the region between Bern and Thun (west of the Aar) 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 Aar 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. 3 shows a depiction of the most important elements in the Wikipedia article along with our delineation of the valley floor. In the western part of the area is the River Gürbe, in the eastern part the river Aar flows out of Lake Thun. North of Belp the Gürbe flows into the Aar which then in turn flows through Bern. As can be seen in Fig. 3, Wikipedia's description of the ridge Belpberg separating the Gürbe valley from the Aar valley somewhat contradicts the assertion that the Gürbe valley is the region bordering the Aar from the west or encompasses the district of Seftigen (whose eastern border is in fact the Aar). However, the width of the Gürbe valley specified by Wikipedia to be 1 to 2 km closely matches the area the DEM-based algorithm delineated as valley floor.

The boxes in Fig. 4 denote the extent of toponym labels mentioned in the Wikipedia article [56] 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 Aar 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.

Although for cartographic reasons toponym labels may not be placed directly over the objects they signify, toponym label locations and the valley floor delineated using our algorithm coincide well. However, the 1:100,000 toponym label of Gürbe valley extends significantly further south than toponym labels from larger scales into a region our 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 [52, 53] lists seventeen municipalities that belong to the Gürbe valley which are shown in Fig. 5 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. 4 – except for the toponym of 1:100,000 which extends considerably further south and the municipality of Rüeggisberg which, judged from the toponyms (Fig. 4) is west of Längenberg.

### 5.2 Comparison with Pixel-Based Morphometric Classification

In order to compare the valley floor delineation method with a pixel-based classification, we computed six morphometric classes [14] for the whole region shown in Fig. 2. We selected a window for implicit surface fitting of between 3 and 7 cells (~300 to 700 metres). In order to determine sensible thresholds for surface gradient and curvature we computed classifications using LANDSERF [57], with curvature threshold of 0.1 and 0.5. We selected a gradient threshold of 1.5° which both gave sensible results and matches the threshold of our region-growing approach.

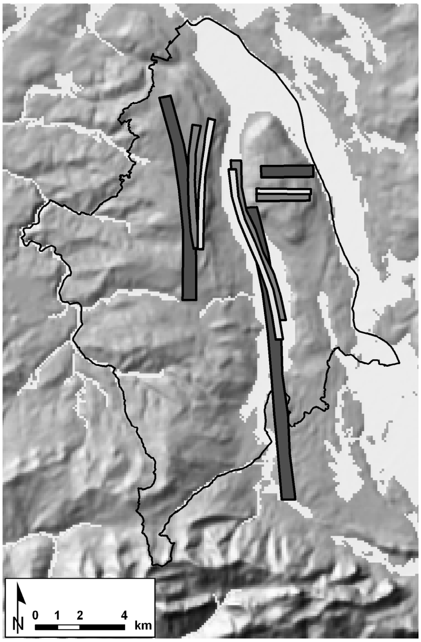


**Fig. 4.** Outline of toponym labels of Swisstopo maps 1:25,000 (lightest), 1:50,000 (medium) and 1:100,000 (darkest grey) referring to Längenberg (west), Gürbe valley (middle) and Belpberg (east). Background: hillshaded DEM, and delineated valley floor, district of Seftigen (black outline) for reference.

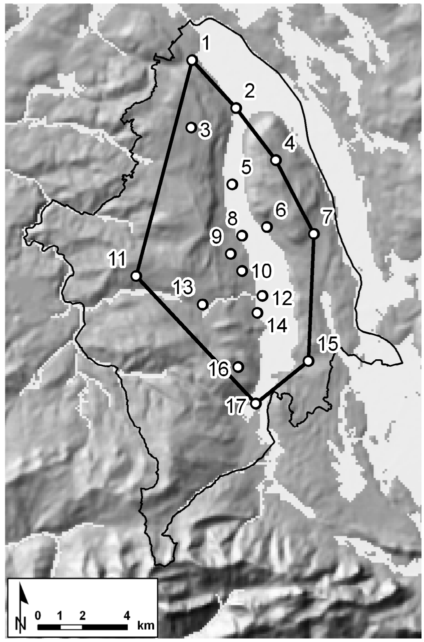


**Fig. 5.** Municipalities listed as belonging to the Gürbe valley by the tourism organisation of the region together with a convex hull (1: Kehrsatz, 2: Belp, 3: Zimmerwald, 4: Belpberg, 5: Toffen, 6: Gelterfingen, 7: Gerzensee, 8: Kaufdorf, 9: Rümligen, 10: Kirchenthurnen, 11: Rüeggisberg, 12: Mühleturnen,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

**Table 1.** Proportions of morphometric classes for region shown in Fig. 2

| | Thresholds in classification | |
|---|---|---|
| | {1.5°; 0.1} | {1.5°; 0.5} |
| Pit | 0.28 % | 0.00 % |
| Channel | 28.93 % | 6.64 % |
| Pass | 1.00 % | 0.01 % |
| Ridge | 28.27 % | 8.03 % |
| Peak | 0.22 % | 0.00 % |
| Planar | 41.30 % | 85.31 % |

Table 1 shows the proportions of each morphometric class for the two curvature values. With a lower threshold curvature the proportion of curved features such as channels, passes or ridges is considerably higher. The adoption of a higher threshold curvature results in an explosion in planar features (85% of the whole region is classified as planar) and we do not further compare values with these thresholds.

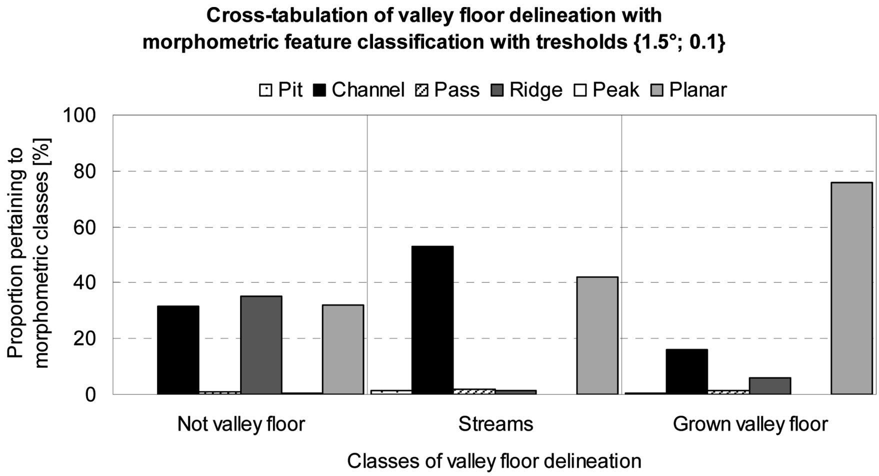


**Fig. 6.** Cross-tabulation statistics of valley floor delineation vs. morphometric feature classification for region shown in Fig. 2 with gradient threshold of 1.5° and curvature threshold 0.1 in the latter

Fig. 6 shows a cross-tabulation between our classification into streams, valley floor and areas not deemed to be valley floor and the six-fold morphometric classification into pit, channel, pass, ridge, peak and planar classes with thresholds {1.5°; 0.1}. 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 (< 2%) occur and to the valley floors where there is a clear dominance of planar pixels, followed by channel (16%) and ridge (6%) pixels.

Figs. 7 and 8 show the spatial arrangement of the delineated valley floor with respect to the morphometric classification and are mutually exclusive since they each depict a part of the six-fold classification but together show all classes except for passes (which are also present in the valley floor).

Fig. 7 shows many channel features on the valley floor, however, their location suggests that these are primarily artifacts occurring near the concavity of the transition from valley floor to side slopes. Pits are found throughout the valley floor, often close to channel features. Fig. 8 shows that there are several instances of ridge pixels and also some peak pixels located within the delineated valley floor mainly (but not exclusively) of the Aar valley. These stem from minor surface undulations which were, from the perspective of some seed pixels, sufficiently smooth to be classified as valley floor.

Summarising, the classifications of morphometric features suggest that the attributes of our valley floors at a pixel level make sense (relative dominance of channel and planar features in streams and valley floors). Furthermore, minor ridges and peaks (which may well be glacial features such as moraines and eskers) are identified by our algorithm as belonging to the valley floor. This suggests a potential strength of object-based top-down approaches over pixel-based methods, 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).

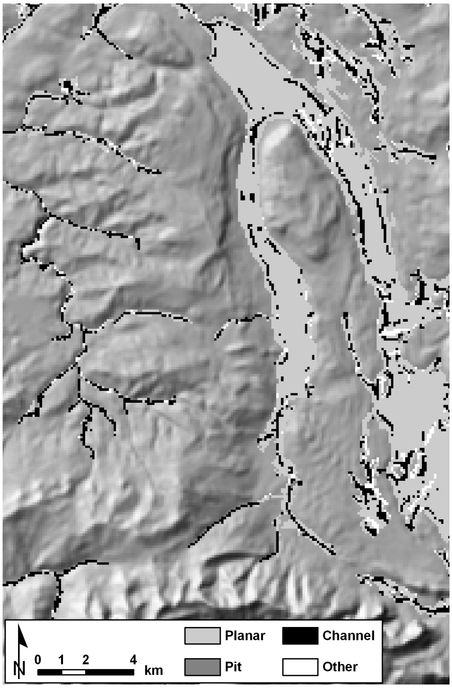


Fig. 7. Planar, pit and channel pixels of classification {1.5°; 0.1} within delineated valley floors

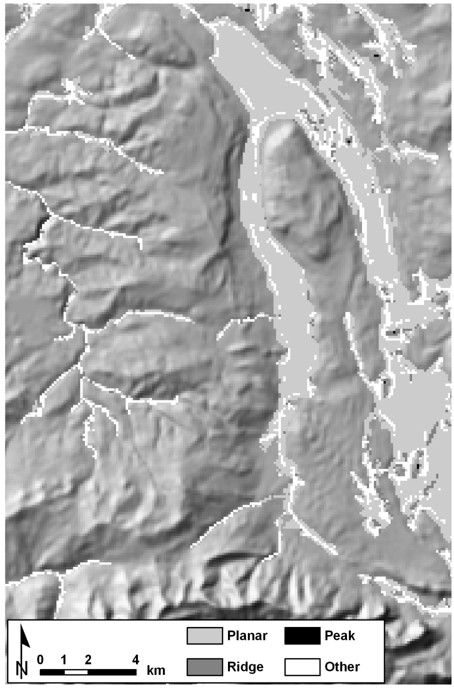


Fig. 8. Planar, ridge and peak pixels of classification {1.5°; 0.1} within delineated valley floors

### 5.3 Limitations and Extensibility of the Approach

An obvious limitation of the approach is the adoption of a single universal gradient threshold for the delineation of valley floors with a region growing algorithm. 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 everywhere else. A possible extension of the approach would select a threshold based upon some contextual information, e.g. 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.

## 6 Conclusions and Outlook

In this paper our key aim was to develop a robust method, capable of deriving valley floor extents over a large area. The developed method is object-based and top-down – that is to say it uses definitions of valley floors in the algorithm development and grows regions which are considered to be valley floor. 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 our 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, we compared our top-down approach to a pixel-based more bottom-up approach which classifies a DEM into six morphometric classes. This comparison showed that our valley floors had differing distributions of morphometric classes from non-valley floor areas (primarily planar slopes and channels), though our algorithm was capable of classifying pixels identified as ridges and peaks as belonging to the valley floor.

It appears that valleys and associated landforms or, more generally, topographic depressions, have gained less attention in the literature than, for example, topographic eminences. We thus intend to continue our current work to delineate valley sides, and thus define the extent of valleys and their relationship to topographic eminences.

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