PFG 2014 / 1, 0041 – 0054
Stuttgart, February 2014

Report

Modification of High Resolution Airborne Laser Scanning DTMs for Drainage Network Delineation

Michael Vetter & Gottfried Mandlburger, Vienna, Austria

Keywords: Hydrology, flow accumulation, open source, GRASS-GIS, anthropogenic effects, street networks, DTM, ALS

Summary: In this paper a method is presented to adapt a 1 m ALS (Airborne Laser Scanning) DTM (Digital Terrain Model) for drainage network delineation. In such DTMs small natural topographic features as well as anthropogenic structures like roads and artificial embankments are contained, both influencing the drainage network delineation process in different ways. While natural topographic features lead water to drainage systems, anthropogenic structures can deflect water alongside artificial surfaces, which are not flow-active under regular hydrological conditions and, therefore, result in wrong drainage systems. We present a workflow to subtract the influence of roads in the DTM, replacing the actual road profile by an average hill slope of the neighbouring terrain. This modified DTM is the basis for drainage network delineation using standard flow accumulation. The drainage networks are derived for four DTM variants (1 m DTM, 1 m modified DTM, 5 m DTM and 5 m modified DTM) and the results are compared to a reference dataset. It is shown that the accuracy of the derived drainage network can be increased by 3–5% using the modified instead of the original 1 m DTM. The gain in accuracy amounts up to 12% when using the modified 1 m DTM compared to any of the 5 m DTM. Therefore, our conclusion is that high resolution and modified 1 m DTMs with anthropogenic structures such as roads strictly removed should be used for drainage network delineation instead of a coarse spatial resolution or an original 1 m DTM.

Zusammenfassung: *Anpassung eines hochauflösenden Airborne Laser Scanning DTMs zur Berechnung von hydrologischen Modellen.* In diesem Artikel wird eine Methode vorgestellt, mit der ein hochauflösendes 1 m ALS (Airborne Laser Scanning) DTM (Digital Terrain Model) für die Ableitung eines potentiellen Gerinnenetzes aufbereitet wird. In 1 m Geländemodellen sind natürliche Geländemerkmale sowie Bereiche mit anthropogener Reliefüberformung (Straßen und künstliche Böschungen) abgebildet. Der natürliche Geländeverlauf und die anthropogenen Strukturen beeinflussen die Ableitung von Gerinnenetzwerken basierend auf Fließakkumulation unterschiedlich. So werden Gerinnenetzwerke entlang des natürlichen Geländeverlaufs in der Regel ein realistisches Gerinnenetzwerk ergeben. Entlang von künstlichen Strukturen können die Berechnungen in eine Richtung abgelenkt werden, in welche unter normalen hydrologischen Bedingungen kein Abfluss stattfindet. Eine solche Ablenkung resultiert daher in einem unrealistischen Gerinnenetzwerk. Mit dem vorgestellten Ansatz, bei dem der Einfluss der Straßen aus dem Geländemodell herausgerechnet und durch eine angenäherte natürliche Neigung entlang der Straßen ersetzt wird, ist eine deutliche Verbesserung der Gerinneableitung möglich. Für vier verschiedene DTM-Varianten werden Gerinnenetzwerke abgeleitet (1 m DTM, modifiziertes 1 m DTM, geglättetes 5 m DTM und modifiziertes 5 m DTM). Die Ergebnisse werden mit einem Referenzdatensatz verglichen, um die Genauigkeit der Ableitung zu dokumentieren. Die endgültigen Resultate der Ableitung und der Qualitätskontrolle ergeben eine Verbesserung der Genauigkeit um 3–5% des modifizierten im Vergleich zum originalen 1 m DTM und eine Verbesserung von bis zu 12% des modifizierten 1 m DTM im Vergleich zum geglätteten bzw. modifizierten 5 m DTM. Folglich ist unsere Empfehlung, für die Ableitung von Gerinnenetzwerken anstatt eines geglätteten 5 m DTM oder eines originalen 1 m DTM ein modifiziertes 1 m DTM zu verwenden, bei dem anthropogene Strukturen wie Straßen rigoros entfernt wurden.

DOI: 10.1127/1432-8364/2014/0208 1432-8364/14/0208 $ 3.50

1 Introduction

For the last two decades, Airborne Laser Scanning (ALS) has become the prime acquisition technique for collecting topographic data in high spatial resolution (> 1 point/m^2) with a height accuracy of less than 15 cm (Wehr & Lohr 1999, Baltsavias 1999), which is used in many different fields of application, e.g. Höfle & Rutzinger (2011), Mandlburger et al. (2009), and Sofia et al. (2011). While countrywide ALS data acquisition is already finished in some European countries, e.g. The Netherlands, Denmark, and Switzerland, some other countries will complete ALS data acquisition in the near future, e.g. Austria and Finland. Almost all European countries maintain river network data derived from low resolution Digital Terrain Models (DTMs) or topographic maps. This is also true for Austria, but the planimetric accuracy and the completeness of the Austrian river network are poor, especially for small catchments. The European Water Framework Directive (WFD, EU 2000) obligates the member countries to provide detailed, up-to-date river network data in high planimetric accuracy with additional attributes per river reach, e.g. length, bed slope, width, and stream ordering. Currently, activities are undertaken to standardize the data exchange on a transnational level. Guidelines for basic datasets have already been implemented (INSPIRE, EU 2007).

The standard drainage delineation methods implemented in proper GIS-Software are based either on single-neighbour flow algorithms (D8, O'Callaghan & Mark 1984) or multiple-neighbour flow algorithms like multiple flow direction (MFD, Quinn et al. 1991). Both flow algorithms are used to compute drainage networks which indicate the potential watercourses. A comprehensive overview about flow algorithms and their differences are given by Gruber & Peckham (2009) and Wilson et al. (2008). Various implementations are available in standard GIS software providing specialized tools for individual environments. Besides flow algorithms, other methods exist to derive drainage networks and features related to hydrology (Passalacqua et al. 2010, 2012).

The differences between drainage network delineation based on high spatial resolution and coarse DTMs are shown in Li & Wong (2010). The quality of a drainage network based on high spatial resolution data, e.g. a 1 m DTM grid, is mainly influenced by man-made objects such as streets and dams, where the flow direction is deflected along the gradient of the street. Remaining bridges or missing objects like culverts or pipes acting as flow barriers, which are not represented in the DTM and yield unrealistic flow paths (Vianello et al. 2009). A DTM free of the above mentioned flow barriers, which additionally guarantees a monotone height progressing along the streams, is referred to as a "hydrologically enforced DTM". Such a DTM is a prerequisite for obtaining correct drainage network results.

2 Objectives

We present a study to map the potential river drainage network system using a high resolution ALS DTM in order to increase the level of detail, correctness and completeness of the final drainage system. Due to the fact that streets produce massive errors for drainage network delineation (Vianello et al. 2009) it is our aim to show the positive impact of manipulating artificial structures in a high spatial resolution ALS DTM on the delineation quality. The goal of this contribution is the derivation of potential river drainage systems. Hereby, the term "potential river" describes the watercourse following the terrain gradient under regular hydrological conditions. At locations where streets block the potential flow path, pipes and culverts are usually built to guarantee a continuous watercourse along ditches. Those pipes and culverts are dimensioned to cope with regular run-off volumes. As regular hydrological conditions are presumed in this article, no deflections alongside the streets are expected. As subsurface man-made structures under roads, e.g. pipes, are undetectable in ALS data, the roads act as walls or barriers if they are not removed from the ALS DTM prior to the drainage delineation. As 1 m DTMs are available in many countries, the goal is to exploit the full potential of those data as source for drainage network delineation, which is not the case up to now (Mandlburger et al. 2011). Therefore, we present a method to modify a DTM by section-wise recalculating the near-natural slope before the road was constructed and by replacing the actual road profile based on the average hill slope. This yields a modified 1 m DTM without streets. The results are compared to a reference dataset provided by the local mapping authority. We assume that the modification of the DTM leads to a better drainage network mapping accuracy when applying automatic delineation based on flow accumulation.

3 Test Site and Data

The chosen test site is a sub-catchment of the Bregenzer Ach (Vorarlberg, Austria) draining the Bregenzerwald. The Bregenzer Ach is an alpine river with an approximate length of 80 km, a total catchment area of 830 km^2, an average annual discharge of 46 m^3/s and a maximum discharge of 1350 m^3/s, which was measured in August 2005, as a 100 year flood event (Amt der Vorarlberger Landesregierung 2005). The selected sub-catchment covers an area of 93 km^2 and is divided into an upper (Bolgenach) and a lower (Weißache) sub-catchment (Fig. 1). The terrain elevations range from 450 m at the confluence of the Weißach and the Bregenzer Ach to 1645 m at the Feuerstätterkopf. The dominant geological formation is Molasse with a dense drainage system (Oberhauser & Rataj 1998).

For the test site ALS data are available from different epochs. For this study the DTM derived from the point cloud, using the hierarchic robust filtering approach described by Kraus & Pfeifer (1998), of the November 2003 campaign, was chosen. The average point density is 1.6 points/m^2 (last echoes). The data were collected with Optech's ALTM 2050 scanner in discrete echo recording with a maximum of four reflections per laser shot. The grid width of the DTM is 1 m. In addition, a resampled version of the DTM with a spatial resolution of 5 m was generated.

Besides the topographic data, a street and a drainage network layer were provided by the local mapping authority (Landesamt für Vermessung und Geoinformation, LVG). The street layer contained several files, each of them representing different street/road types such as high order streets, municipal roads,

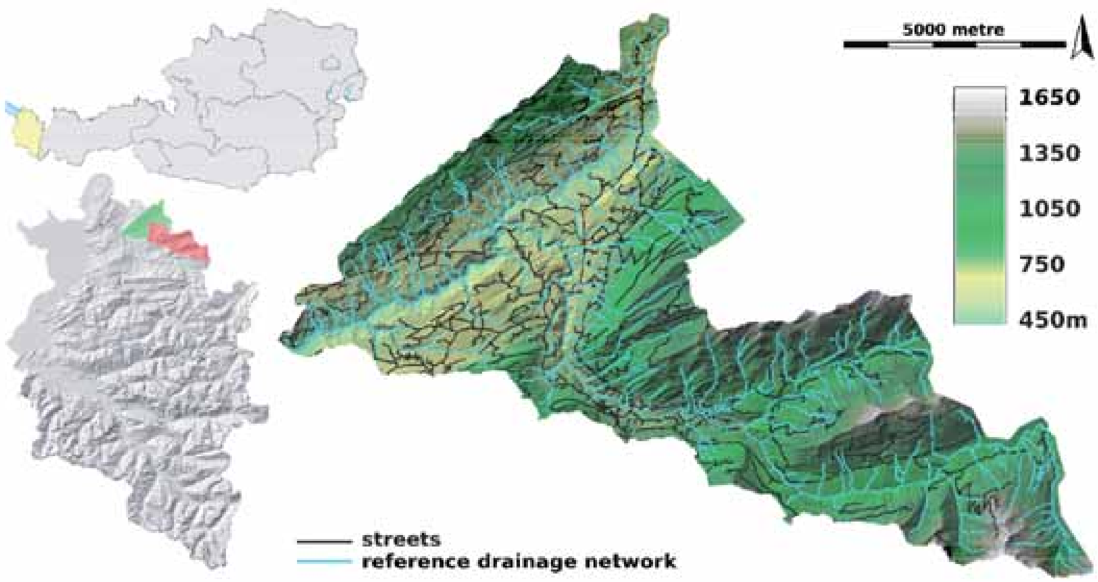

Fig. 1: Test site (Bregenzerwald, Vorarlberg, Austria); shading superimposed with elevation coding, roads and existing river network. Left: map of Vorarlberg with the upper (red) and lower (green) sub-catchments of the Bregenzer Ach. Map sources: Austria: Wikimedia.ogr as svg; Vorarlberg: http://vogis.cnv.at/ (WMS); catchments, streets and official drainage network: Landesamt für Vermessung und Geoinformation (LVG, Amt der Vorarlberger Landesregierung).

forest roads or hiking trails. The layers were produced by different departments within the authority of Vorarlberg on the basis of orthophotos and shaded relief maps of the 1 m DTM. Before the actual processing, a consistency check was performed by visual inspection and the different layers were merged into a single dataset. It could be verified that the deviation of the street locations compared to the shaded relief map of the 1 m ALS DTM is less than 5 m.

The reference drainage network dataset was provided by the local hydrology and geoinformation department (Abteilung Wasserwirtschaft, Landesamt für Vermessung und Geoinformation). It was mapped in a semi-automatic way by deriving the main drainage network using standard flow accumulation methods based on the 1 m ALS DTM from 2003. The resulting vector dataset was interactively edited using orthophotos and 1 m shaded relief maps to improve the correctness and completeness of the dataset. This reference dataset also includes all culverts, piped sections under bridges and fictitious river axes through lakes. The provided reference drainage network is constantly improved and entirely supervised by hydrology experts and is the best available dataset covering the entire area of one single federal state in Austria. The latest timestamp of the river network reference data is October 10, 2012. Those data are used for evaluating the presented methods. Although there is a time difference between the ALS DTM and the reference dataset, this time gap is of minor importance, because no streets have been built and no major mass movements or other natural hazards have occurred since the time the ALS data were acquired in 2003. Only in one part a huge landslide is currently active but in this area no streets are located.

4 Methods

The method relies on two datasets. The first dataset is the ALS DTM, which is used as basic input for the processing workflow presented later, and for drainage network delineation. The second dataset is a vector (polyline) layer representing the axes of the existing streets. Wherever possible, street data from the local mapping authorities should be used, because these datasets are usually well maintained in Europe concerning both, accuracy and up-to-dateness. If no such official data source is available, street layers can also be extracted from OpenStreetMap (OSM) or obtained from commercial navigation and routing system providers with an expected lower accuracy. If no centre lines of the streets are available, the street edges can be derived by using a multi-scale segmentation approach (Baatz et al. 2003), raster-based classification using elevation, slope, aspect and curvature (first and second order derivatives) as shown in Wood (1996), Brügelmann (2000) or Rutzinger et al. (2011) or breakline modelling based on the ALS point cloud, e.g. Briese (2004). The resulting street edges can be used to obtain the centre lines.

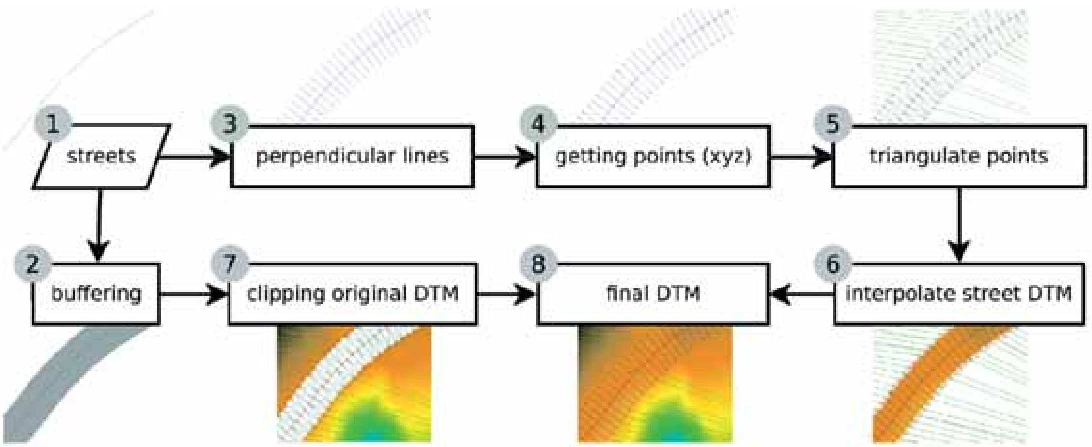

Fig. 2: Workflow and processing chain for DTM modification.

Our workflow is shown in Fig. 2. First, the centre lines of the streets (1) are buffered to define the extent for DTM modification (2). Then, perpendicular lines (cross sections) with a fixed distance from each other along the street axis and a predefined length are created (3). For each cross section the heights of the start and end points are interpolated from the DTM and the height of the centre point is calculated by linear interpolation from the start and end points, resulting in three X,Y,Z coordinate triples (4) for each cross section. After that, all extracted start, centre, and end points of a single street line are triangulated (5) and from the resulting TIN a regular grid of the buffer area (6) is derived, representing the reconstructed model of the terrain with near-natural slope. Finally, the buffer from step (2) is used to clip the DTM (7) and, by a map algebra operation, the clipped DTM and the reconstructed surface along the street are fused to the modified DTM (8), containing no streets.

5 Experiments

The method described in the previous section was applied to the original 1 m DTM described above, yielding a modified DTM of 1 m resolution. To simulate the influence of a coarser resolution on the final drainage network product, both the original and the modified 1 m DTM were down-sampled to a spatial resolution of 5 m by applying a moving average filter. As a consequence, four different DTMs are used in our experiments (original 1 m DTM, modified 1 m DTM, 5 m DTM, and modified 5 m DTM).

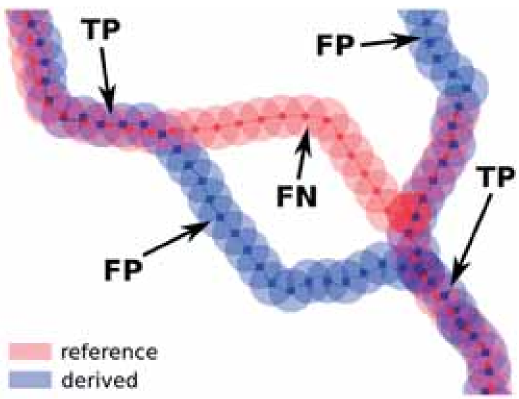

Fig. 3: Classification of the nodes of the derived and reference network into True Positives (TP), False Positives (FP) and False Negatives (FN); schematic diagram.

For drainage network delineation, a standard flow accumulation method based on Multiple Flow Directions (MFD), as implemented in GRASS-GIS (r.stream.extract, Jasiewicz & Metz 2011, GRASS Development Team 2012), is used to compute the drainage network.

For the error assessment a line based approach as described in Rutzinger et al. (2012) is chosen. For each dataset, i.e. reference and the derived drainage network, we interpolate points along the lines at a regular interval, and we replace the lines by these (dense) point sets. The evaluation procedure is based on an analysis of the reference and the derived drainage point sets. Points from both datasets are accepted as corresponding (True Positives, TP) if they are within a defined search radius (Fig. 3). False Positives (FP) denote points of the derived dataset for which no corresponding point in the reference exists. Points of the reference with no corresponding point in the derived dataset are counted as False Negatives (FN). Correctness (1), completeness (2) and quality (3) are calculated for selected search radii (1 m, 5 m, 10 m, and 15 m), taking into account the numbers of TP, FP and FN, respectively.

$$\text{Correctness} = \frac{TP}{TP + FP} \tag{1}$$

$$\text{Completeness} = \frac{TP}{TP + FN} \tag{2}$$

$$\text{Quality} = \frac{TP}{TP + FP + FN} \tag{3}$$

6 Results

In this section we present the results of data processing (DTM modification) as well as the comparison of the different drainage networks obtained by using the four DTM variants described in section 5. The comparison is carried out both, by visual inspection of the derived drainage networks and by a statistical analysis of the accuracy with respect to the reference data.

6.1 *DTM Modification*

The parameters required for the DTM modification are a) the buffering distance, b) the cross section distance along the street axis, and c) the length of the cross sections. The buffering distance a) is strongly related to the cross section length c), because the length c) has to be larger than the buffering distance to guarantee that no void data areas are produced during data fusion, e.g. Fig. 2, step 8. The cross section distance b) controls the granularity of the interpolated slopes and therefore should be kept small. The parameters used in our experiments are a): 7 m buffering distance, resulting in a buffer width of 14 m, which corresponds to the width of a street having four lanes; b): 3 m profile distance along the road axes; c): 16 m length of the profiles. During the workflow (Fig. 2, step 4) the X,Y,Z coordinates of the start, centre and end points of the cross sections are triangulated.

Fig. 4 shows the colour coded height differences between the original and the modified 1 m DTM for a short street section. Plots of three cross sections (A, B, C) illustrate the effect of the DTM modification. In the plots the original DTM is shown in blue and the modified profile in red. The modified surface represents the natural slope before road construction. The interpolation is carried out for all streets and roads of the provided street layer, which results in a modified DTM approximating the original slope. This modified DTM is the basis for the further calculations of the drainage network. The modified 5 m DTM is calculated by resampling the modified 1 m DTM.

6.2 *Drainage Derivation*

As a precondition for the subsequent derivation of the drainage network the Multiple Flow Direction was calculated for all four DTMs.

The parameters for drainage network delineation are I) minimum catchment area (2.5 ha) and II) minimum segment length (> 100 m). These parameter values are applied to all DTMs to produce comparable results. A discussion about different drainage delineation parameters is not given in this article, because

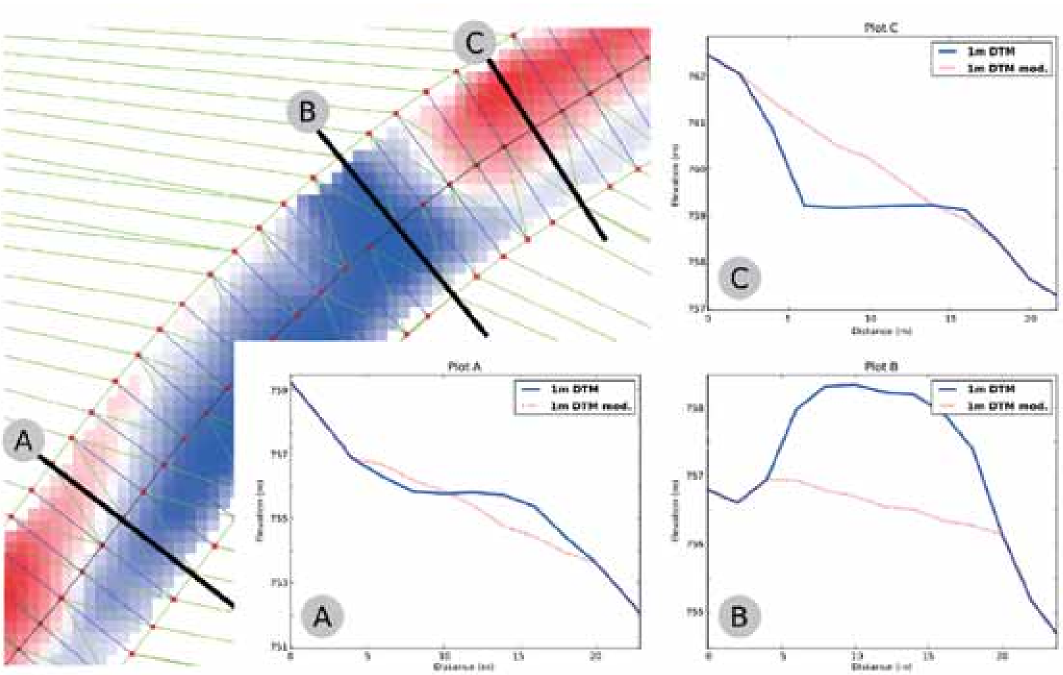

Fig. 4: Difference between original and modified 1 m DTM with street centre line (black), cross sections (blue), interpolation points (red) and triangulation (green); sections through original and modified DTM (DTM blue solid line, modified DTM red dashed line).

this is discussed in numerous papers, e.g. Wilson et al. (2008). Our focus is on presenting the advantages of using a modified 1 m DTM for deriving drainage systems, not on optimizing parameters for drainage delineation.

The drainage networks based on the four different DTM variants are shown in Fig. 5. It is clearly visible that the original 1 m DTM results in many drainage segments alongside the streets (Fig. 5a). A drainage segment is a part of the stream network between two nodes (nodes are intersection points, confluence points, source or end points). These problems are reduced but not completely removed by using a resampled 5 m DTM (Fig. 5b). Using the proposed DTM modification, the artificial flow patterns along the streets are more effectively removed, and at the same time a high level of detail is preserved (Fig. 5c). The use of a modified 5 m DTM (Fig. 5d) shows no deflection at all along the roads.

Fig. 5 also reveals that the deflection of delineated drainage segments is higher for the original 1 m and the 5 m DTMs than for both modified models. By resampling the DTM, small but sometimes relevant terrain features are removed. If an important terrain feature is removed, the direction of the drainage can be changed dramatically and can result in a wrong final network. This phenomenon can be seen in Figs. 5b and 6a alike. The level of detail of the derived drainage network also decreases if a 5 m DTM is used. On the one hand, the lengths of the source segments decrease and on the other hand, the spatial resolution and, therefore, the stream mapping accuracy also decreases.

6.3 *Accuracy of the Derived Drainage Network*

In this section we present the accuracy of the derived drainage network with respect to the reference data. For the quantitative assessment all piped and fictitious river segments (7.5% of

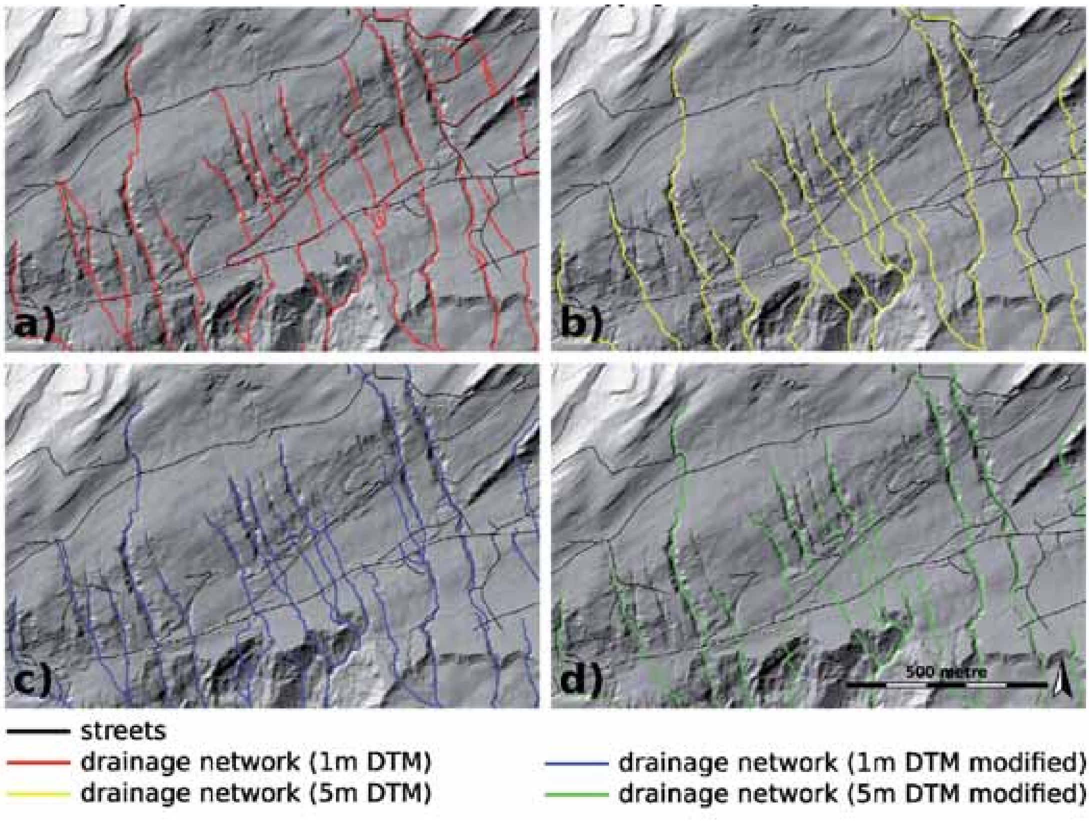

Fig. 5: Drainage network based on original and modified DTMs (1 m, 5 m). a) 1 m DTM; b) resampled 5 m DTM; c) modified 1 m DTM; d) modified 5 m DTM.

the original reference data) have been excluded from the reference network. As can be seen in Fig. 6a, the test site contains piped sections, mainly alongside roads, and, consequentially, the reference dataset does show some flow paths following the course of the road. In these specific cases the piped sections are measures to prevent mass movements. Usually, piped sections are built as shortest possible conduit across the road to allow water flow under the road. Our approach is designed to deal with that normal kind of underpass conductor but not with piped sections along the road. Therefore, this particular part of the reference data was neglected for the quantitative evaluation.

A visual comparison of the derived drainage system of both modified DTMs (1 m and 5 m) and the reference is presented in Fig. 6a. The correspondence of the derived drainage network based on the modified 1 m DTM is satisfactory. A few locations at the stream head are generally missing in the reference network, where the stream head is close to the catchment boundary. This results from the used catchment area threshold for drainage network delineation. It can be stated that the additional flow length in upstream direction provided by the automatic delineation process is useful information although it is not covered in the reference. As can be seen in Figs. 6a and 6b, the drainage network derived from the modified 1 m DTM delivers more streams than are contained in the reference network. The fact that these extra streams are contained in the derived dataset means that they are well pronounced in the DTM. But this does not necessarily mean, that they are permanently drained, for which reason the expert responsible for the reference dataset may have disregarded them as relevant rivers. At least, in case of major precipitation events, these streams are likely to contribute to the surface runoff.

The cumulative lengths of the reference data and the derived drainage networks are analysed in Tab. 1. The derived network based on the original and the modified 1 m DTM is more than twice as long as the reference (Fig. 6) and the drainage based on both 5 m models are approximately 1.4 times longer than the reference. A small part of the differences in lengths stems from the zig-zag patterns in the derived data caused by rasterisation. However, most of the differences are due to a higher number of drainage segments in the derived datasets and their extended length compared to the reference.

For the quantitative error assessment, a point spacing of 1 m is used for all drainage networks and the reference data. The percentages of completeness, correctness and the quality are shown in Tab. 2.

7 Discussion

The presented method for DTM modification, using existing street data to replace and remodel near-natural slopes along the roads, uses a global constant street buffer width. A global width was chosen as the GIS metadata of the roads does not entirely contain road classification information. It is assumed that buffering taking into account different street widths could increase the quality of the DTM modification process. As shown in Tab. 2, the completeness of the derived river network is much better than the correctness for all considered DTM variants when taking into account all derived stream segments, i.e., all drainage sections between two nodes, section 6.2. The completeness is almost the same for both 1 m models, but there is a difference of up to 17% between the 1 m and the 5 m DTMs. On the other hand, the correctness and the quality are much better for the 5 m models. The lower correctness of both 1 m DTMs basically stems from the higher number of automatically derived streams and their extended length, both, with respect to the 5 m DTMs and the reference. The added value of these extra streams was already discussed in section 6.

Tab. 2 clearly shows a moderate and unsatisfactory quality. However, this global comparison using the entire automatically derived network is unjustified as rivers of minor importance for the countrywide river network were deliberately ignored by the human operator providing the reference network. To improve the comparability, three subsets of the derived network were compiled and analyzed independently with respect to completeness, correctness and quality. The subsets are

Tab. 1: Cumulative length of networks entire reference data, revised reference data (fictitious and piped sections removed) and derived networks based on original and modified DTM (1 m & 5 m).

Data	Reference	Reference subset	1 m DTM	1 m DTM modified	5 m DTM	5 m DTM modified
Length (m)	246,163	227,688	518,250	495,106	353,501	346,980
Percentage	100.0	92.5	210.5	201.1	143.6	141.0

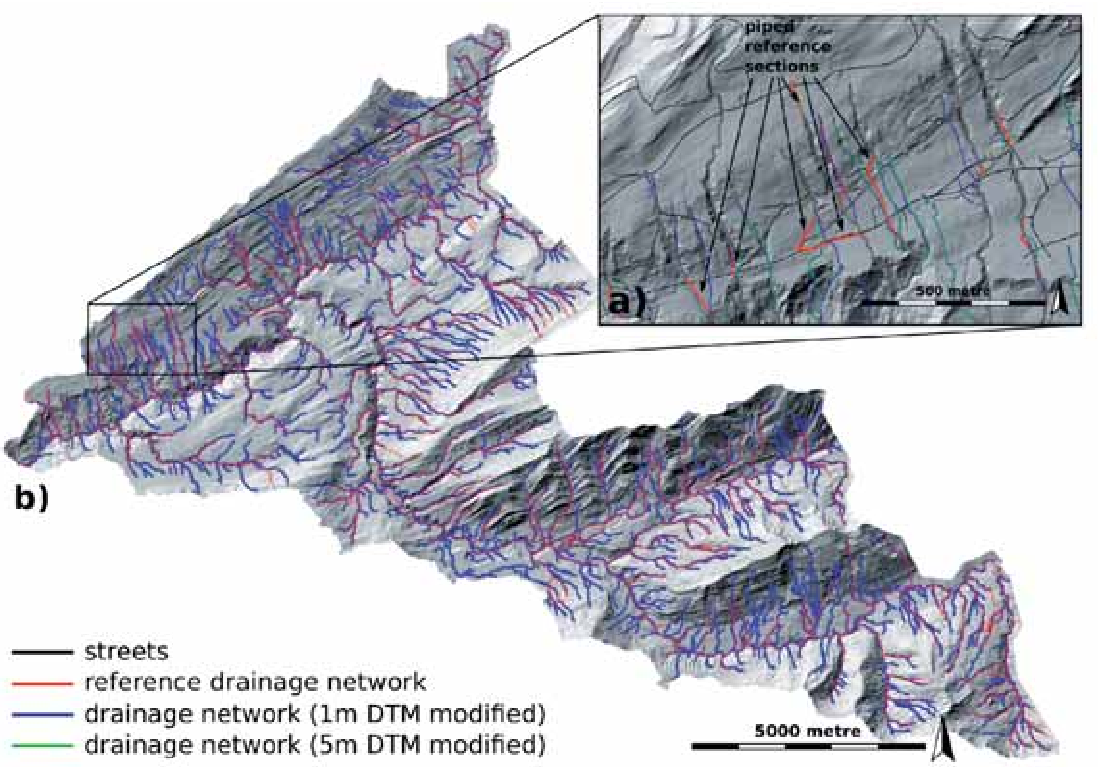

Fig. 6: Results of drainage network delineation. a) From modified 5 m DTM (green), modified 1 m DTM (dark blue) and the reference network (red); b) Drainage network of the entire test site derived from modified 1 m DTM and reference data. Piped reference sections are marked.

Tab. 2: Error assessment (completeness, correctness and quality); complete drainage network compared with revised reference data.

	1 m radius			5 m radius			10 m radius			15 m radius		
All segments	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**
DTM 1 m	0.50	0.21	0.17	0.85	0.35	0.33	0.90	0.37	0.35	0.92	0.38	0.36
DTM 1 m modified	**0.50**	**0.22**	**0.18**	**0.86**	**0.37**	**0.35**	**0.91**	**0.39**	**0.38**	**0.92**	**0.40**	**0.39**
DTM 5 m	0.33	0.20	0.14	0.78	0.47	0.42	0.83	0.50	0.46	0.85	0.51	0.47
DTM 5 m modified	0.33	0.20	0.14	0.79	0.48	0.43	0.84	0.51	0.47	0.86	0.53	0.48

introduced step by step with the final goal to restrict the nominal-actual comparison to the vindicated parts.

First, all extra segments of the derived dataset located entirely outside a 20 m perimeter around the reference network were excluded (Selection I, blue lines in Fig. 7a). Additionally, all major rivers featuring a width larger than 20 m, i.e. the Weißache and the Bolgenache, were removed (selection II, cf. blue lines in Fig. 7b). Finally, based on Selection II the detailed area shown in Fig. 6a was analysed separately (Selection III). Hereby, the reference data segments were compared to the spatially correlating parts of the derived segments, i.e. the derived segments were cut to the same lengths as the reference. In this way, all parts of the derived segments (i) corresponding to piped sections of the reference or (ii) extending the reference near the source were removed (blue lines in Fig. 7c spatially corresponding to the red lines in Fig. 7d).

Tab. 3 shows that the completeness is higher for the derived drainage network using the modified 1 m DTM than for the drainage derived based on the original 1 m or both 5 m

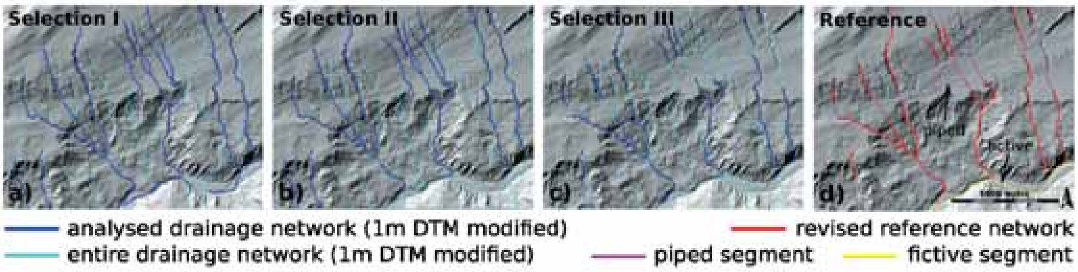

Fig. 7: Subsets of the river network derived from modified 1 m DTM (a-c, blue lines corresponding to Selection I-III) and reference data (d, red lines).

Tab. 3: Error assessment (completeness, correctness and quality) for Selection I, II and III (Fig. 7).

	1 m radius			**5 m radius**			**10 m radius**			**15 m radius**		
Selection I	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**
DTM 1 m	0.49	0.36	0.26	0.83	0.61	0.54	0.88	0.65	0.60	0.90	0.66	0.62
DTM 1 m modified	**0.49**	**0.38**	**0.27**	**0.85**	**0.65**	**0.58**	**0.90**	**0.68**	**0.63**	**0.91**	**0.70**	**0.65**
DTM 5 m	0.32	0.27	0.17	0.77	0.65	0.54	0.82	0.69	0.60	0.84	0.71	0.62
DTM 5 m modified	0.33	0.27	0.17	0.78	0.65	0.55	0.84	0.69	0.61	0.86	0.71	0.64
	1 m radius			**5 m radius**			**10 m radius**			**15 m radius**		
Selection II	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**
DTM 1 m	0.54	0.40	0.30	0.85	0.63	0.57	0.80	0.65	0.59	0.89	0.66	0.61
DTM 1 m modified	**0.55**	**0.42**	**0.31**	**0.87**	**0.67**	**0.61**	**0.89**	**0.69**	**0.64**	**0.90**	**0.70**	**0.65**
DTM 5 m	0.34	0.29	0.19	0.77	0.66	0.55	0.80	0.68	0.58	0.81	0.69	0.60
DTM 5 m modified	0.35	0.29	0.19	0.79	0.65	0.56	0.82	0.68	0.59	0.84	0.69	0.61
	1 m radius			**5 m radius**			**10 m radius**			**15 m radius**		
Selection III	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**	**comp.**	**corr.**	**quality**
DTM 1 m modified	**0.63**	**0.55**	**0.41**	**0.97**	**0.84**	**0.83**	**0.99**	**0.86**	**0.85**	**0.99**	**0.86**	**0.86**

DTMs. The correctness is higher for the modified 1 m DTM compared to the other DTMs within the 1 m search radius (Tab. 2). If the main river is included (Tab. 2 and Tab. 3, selection I) in the evaluation, the correctness of the streams based on the coarse resolution DTMs is higher. In Tab. 3, both, correctness and completeness are higher for the 1 m modified DTM streams. The correctness (in Tab. 2) is much lower than the completeness, because piped sections and fictive river axes through lakes and large rivers have deliberately been removed from the reference dataset as mentioned in section 6. Due to our DTM modification these parts are contained in the derived dataset, causing a high level of FP and, consequently, a low correctness. Furthermore, the automatic delineation algorithm produces more streams (Tab. 1) than are contained in the reference, which further contributes to the low correctness. This does not necessarily mean that the automatically derived network is incorrect, but a separation into parts where the derived network really deviates from the reference and extends the reference is necessary.

For that reason the quality assessment was carried out for Selection I, II and III. Selection I considers the fact that the automatic process delivers more streams and that rivers in subcatchments are contained, where they have been disregarded in the reference. For the 5 m search radius, the increase in correctness is more than 25% for the original and modified 1 m DTMs (Tab. 2: 0.35/0.37 vs. Tab. 3/Selection I: 0.61/0.65). Selection II deals with rivers wider than 20 m, where the employed flow accumulation based delineation procedure is not the method of first choice. For streams of that size, the planimetric accuracy of the river axis based on flow accumulation is low as the derived line is meandering. For deriving accurate centre lines of such rivers more suitable approaches exist, e.g. Höfle et al. (2009) and Vetter et al. (2011). The additional increase is 2% for both 1 m DTMs. Selection III additionally takes into account that (i) underground piped sections are built more or less straight and not following the surficial discharge and (ii) that the derived source segments generally extend their counterpart in the reference network near the river head. This subset represents a commensurable basis of the reference and the derived dataset. Again, for the 5 m search radius the correctness of the modified 1 m DTM rises to 84%.

From Tab. 3 it can be seen that the correctness gradually increases from Selections I to III. Furthermore, an increase of the correctness is noticeable from 1 m search radius to 5 m, but larger search radii do not lead to a further improvement. From that observation we conclude that the planimetric accuracy of the derived network is in the metre range. Concerning the different DTM variants, it can be stated that whereas Tab. 2, i.e. all derived segments, exhibits higher correctness for the coarse resolution DTMs, the modified 1 m DTM strictly outperforms the other DTMs in Tab. 3. This is the reason why the evaluation for Selection III was only carried out for this DTM variant. The accuracy of the derived drainage network as measured by the completeness, the correctness and the quality of the results, is on average 3 to 5% higher when using the modified DTM rather than the original 1 m DTM. We consider a 3 to 5% increase in quality as a relevant improvement. It is crucial to mention that not all man-made structures necessarily have high impact on the natural run-off. In other words, in most cases the run-off is dominated by the overall natural relief. Thus, the improvement potential in terms of completeness, correctness and quality is within narrow bounds, but nonetheless the remaining 5% improvement may locally make a big difference. Comparing the results achieved for the modified 1 m DTM with those achieved using the DTM at a lower resolution; the average is between 1% and 12% better using the modified DTM. The main differences between the results based on DTMs of 1 m and 5 m resolution occur in the completeness and only minor differences occur in the correctness. By using coarse resolution input data, the possibility of deflecting the derived run-off is much more evident. Some terrain features are removed due to the resampling process. Therefore, the flow accumulation follows a wrong slope, e.g. drain to a neighbouring valley, Fig. 6a. As this increases the necessary manual editing effort, the proposed method facilitates the drainage network delineation process.

8 Conclusion

For the derivation of a river network based on standard flow accumulation techniques a hydrologically enforced DTM without barriers hindering the run-off is required. The available high resolution DTMs do not fulfil this prerequisite as they contain objects like bridges and street dams acting as flow barriers. In this contribution we therefore presented an approach to automatically modify the DTM within a buffer zone around streets. Dams, cuttings and bridges are removed and the near-natural slope before anthropogenic relief transformation is approximated.

The drainage networks derived from the original and modified 1 m DTM as well as for downsampled 5 m models were compared with reference data manually digitized by hydrology experts. It could be shown that the overall accuracy gain is 3–5% when using the modified instead of the original 1 m DTM and 12% compared to the down-sampled 5 m DTM. Whereas the down-sampling of the high resolution DTM speeds up the delineation process, this potentially results in incorrect deflections of the run-off. The availability of topographic details contained in the 1 m DTM are especially important near the catchment boundaries.

The presented DTM modification strategy is designed for regular discharge condition, i.e. mean-flow, where the upstream waters fully drain-off under the streets via piped sections. In our approach, the impact of these piped sections is simulated by the applied DTM modification. Beyond that, additional hydrologically relevant constructional measures exist, e.g., to stabilize slopes prone to landslides via piped sections alongside the slopes and/or streets. As these features are invisible in the DTM, they are generally not available for the flow accumulation based river network derivation. This results in deviations of the derived network from the reference and in a decreased accuracy in these areas. As a consequence, manual editing of the final streams by an expert becomes necessary whenever the data basis does not fulfil the requirements of a hydrologically enforced DTM. However, it can be concluded that the proposed method contributes to reduce the manual editing effort and, therefore, increases, both, the reproducibility and the efficiency of the river network derivation process.

Acknowledgements

The authors want to thank the "Landesamt für Vermessung und Geoinformation" of Vorarlberg, Austria, namely to Peter Drexel for providing the DTM as well as the reference dataset of the drainage network. Thanks also go to our colleagues Bernhard Höfle of the University of Heidelberg, Germany, and Martin Rutzinger from the University of Innsbruck for supporting the accuracy measure calculation. This study was co-funded by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (Project: BlMLFUW-UW.3.2.5/0040-VII/2010). We would also like to acknowledge the financial support from the Austrian Science Funds (FWF) as part of the Vienna Doctoral Programme on Water Resource Systems (DK-plus W1219-N22), the Austrian Science Promotion Agency (FFG-COMET) project "Alpine Airborne Hydromapping – from research to practice" (AAHM-R2P), the Austrian Climate and Energy Fund – ACRP Program – Climate induced system status changes at slopes and their impact on shallow landslide susceptibility (C3S-ISLS) and the Institute of Geography, University of Innsbruck.

References

Amt der Vorarlberger Landesregierung, 2005: Das Starkregen- und Hochwasserereignis des August 2005 in Vorarlberg. – Amt der Vorarlberger Landesregierung, www.vorarlberg.at/pdf/naturereignisdokumentatio.pdf (10.11.2013).

Baatz, M., 2003: eCogniction – user guide 3, Definiens Imaging GmbH.

Baltsavias, E.P., 1999: Airborne laser scanning: basic relations and formulas. – ISPRS Journal of Photogrammetry & Remote Sensing **54** (2–3): 199–214.

Briese, C., 2004: Three-dimensional Modelling of Break lines from Airborne Laser Scanner Data. – IAPRS **35** (B3): 1097–1102.

Brügelmann, R., 2000: Automatic breakline detection from airborne laser range data. – IAPRS **33** (B3): 109–116.

EU, 2000: Water Framework Directive, 2000/60/EC. – Official Journal of the European Union (OJL) **327:** 173.

EU, 2007: Infrastructure for Spatial Information in the European Community (INSPIRE). – Directive 2007/2/EC, Official Journal of the European Union (OJL) **50:** 114.

GRASS Development Team, 2012: Geographic Resources Analysis Support System (GRASS GIS) Software. – Open Source Geospatial Foundation, http://grass.osgeo.org (1.12.2012).

Gruber, S. & Peckham, S., 2009: Chapter 7 Land-Surface Parameters and Objects in Hydrology. – Hengl, T. & Reuter, H.I. (eds.): Geomorphometry Concepts, Software, Applications, 171–194, Elsevier, 2009.

Höfle, B., Vetter, M., Pfeifer, N., Mandlburger, G. & Stötter, J., 2009: Water surface mapping from airborne laser scanning using signal amplitude and elevation data. – Earth Surface Processes and Landforms **34:** 1635–1649.

Höfle, B. & Rutzinger, M., 2011: Topographic airborne LiDAR in geomorphology: A technological perspective. – Zeitschrift für Geomorphologie/Annals of Geomorphology **55:** 1–29.

Kraus, K. & Pfeifer, N., 1998: Determination of terrain models in wooded areas with airborne laser scanner data. – ISPRS Journal of Photogrammetry & Remote Sensing **53:** 193–203.

Jasiewicz, J. & Metz, M., 2011: A new GRASS GIS toolkit for Hortonian analysis of drainage networks. – Computers and Geosciences **37** (8): 1162–1173.

Li, J. & Wong, D.W.S., 2010: Effects of DEM sources on hydrologic applications. – Computers, Environment and Urban Systems **34** (3): 251–261.

Mandlburger, G., Hauer, C., Höfle, B., Habersack, H. & Pfeifer, N., 2009: Optimisation of LiDAR derived terrain models for river flow modelling. – Hydrology and Earth System Sciences **13:** 1453–1466.

Mandlburger, G., Vetter, M., Milenkovic, M. & Pfeifer, N., 2011: Derivation of a countrywide river network based on Airborne Laser Scanning DEMs. – Results of a pilot study Modelling and Simulation Society of Australia and New Zealand: 2423–2429.

O'Callaghan, J.F. & Mark, D.M., 1984: The extraction of drainage networks from digital elevation data. – Computer Vision, Graphics and Image Processing **28:** 328–344.

Oberhauser, R. & Rataj, W., 1998: Geologisch-Tektonische Übersichtskarte Vorarlberg 1:200.000. Wien, Geologische Bundesanstalt.

Passalacqua, P., Trung, T.-D., Foufoula-Georgiou, E., Sapiro, G. & Dietrich, W.E., 2010: A geometric framework for channel network extraction from lidar: nonlinear diffusion and geodesic paths. – Journal of Geophysical Research – Earth Surface **115:** F01002, doi:10.1029/2009JF001254.

Passalacqua, P., Belmont, P. & Foufoula-Georgiou, E., 2012: Automatic geomorphic feature extraction from lidar in flat and engineered landscapes. – Water Resources Research **48:** W03528; doi:10.1029/2011WR010958.

Quinn, P.F., Beven, K.J., Chevallier, P. & Planchon, O., 1991: The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. – Hydrological Processes **5:** 59–79.

Rutzinger, M., Höfle, B., Vetter, M. & Pfeifer, N., 2011: Digital terrain models from airborne laser scanning for the automatic extraction of natural and anthropogenic linear structures. – Smith, M., Paron, P. & Griffiths, J.S. (eds.): Geomorphological Mapping: a professional handbook of techniques and applications: 475–488, Elsevier.

Rutzinger, M., Höfle, B. & Kringer, K., 2012: Accuracy of automatically extacted geomorphological breaklines from airborne LiDAR curvature images. – Geographiska Annaler: Series A, Physical Geography **94:** 33–42.

Sofia, G., Tarolli, P., Cazorzi, F. & Dalla Fontana, G., 2011: An objective approach for feature extraction: distribution analysis and statistical descriptors for scale choice and channel network identification. – Hydrology and Earth System Sciences **15** (5): 1387–1402.

Vetter, M., Höfle, B., Rutzinger, M. & Mandlburger, G., 2011: Estimating changes of riverine landscapes and riverbeds by using airborne LiDAR data and river cross-sections. – Zeitschrift für Geomorphologie/Annals of Geomorphology **55:** 51–65.

Vianello, A., Cavalli, M. & Tarolli, P., 2009: LiDAR-derived slopes for headwater channel network analysis. – CATENA **76** (2): 97–106.

Wehr, A. & Lohr, U., 1999: Airborne laser scanning – an introduction and overview. – ISPRS Journal of Photogrammetry & Remote Sensing **54** (2–3): 68–82.

Wilson, J.P., Aggett, G.R., Deng, Y.X. & Lam, C.S., 2008: Water in the landscape: a review of contemporary flow routing algorithms. – Zhou, Q., Lees, B. & Tang, G. (eds.): Advances in Digital Terrain Analysis: 213–236, Springer.

Wood, J.D., 1996: The geomorphological characterisation of digital elevation models. – PhD Thesis, University of Leicester, United Kingdom.

Addresses of the Authors:

Mag. Dr. Michael Vetter, 1.) Research Groups Photogrammetry & Remote Sensing, Department of Geodesy and Geoinformation, Vienna University of Technology (TUW), Austria; 2.) CWRS – Centre for Water Resource Systems, TUW; 3.) Institute of Geography, University of Innsbruck, Austria, e-mail: office.michael.vetter@gmail.com

DI Dr. Gottfried Mandlburger, Research Groups Photogrammetry & Remote Sensing, Department of Geodesy and Geoinformation, Vienna University of Technology, Austria, Tel. 0043-1-58801-12235, e-mail: gottfried.mandlburger@geo.tuwien.ac.at

Manuskript eingereicht: Februar 2013
Angenommen: November 2013