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Resolution Sensitivity of a Compound Terrain Derivative as Computed from LiDAR-Based Elevation Data

Ralph K. Straumann and Ross S. Purves

Department of Geography, University of Zurich – Irchel,
Winterthurerstrasse 190, CH-8057 Zurich, Switzerland
{rsm, rsp}@geo.unizh.ch

Abstract. New technologies such as Light Detection And Ranging (LiDAR) provide high resolution digital elevation data. These data offer new possibilities in the field of terrain modelling and analysis. However, not very much is known about the effects when these data are used to compute broadly applied terrain derivatives. In this paper the sensitivity of the Topographic Wetness Index (TWI) and its two constituting components gradient and Specific Catchment Area (SCA) regarding the resolution of LiDAR-based elevation data is examined. For coarser resolutions a shift in the TWI distribution to higher values is noted. TWI distributions at different resolutions differ significantly from each other. These findings have an impact on aspatial and spatial modelling based on the TWI.

Keywords: Terrain derivatives, Topographic Wetness Index, resolution sensitivity, LiDAR

1 Introduction

In recent years new technologies for acquiring high resolution digital elevation data have become increasingly widely available, e.g. LiDAR [1]. For example, in Switzerland LiDAR data are being collected for all areas below 2000 m. This rapid increase in the availability of such high resolution data provides an opportunity and a need for GIScience to reexamine the implications of high resolution data. This paper investigates the effects of such data in the field of terrain analysis by exploring a widely used compound topographic index, the Topographic Wetness Index (TWI). The TWI is defined as the natural log of the ratio of the Specific Catchment Area (SCA; upslope area per unit contour length) A_s and the tangent of the gradient at a given location [2]:

$$TWI_{(x,y)} = \ln\left(A_s / \tan\beta\right). \quad (1)$$

One of the most common uses of TWI is within the rainfall-runoff model TOPMODEL [3]. Since TOPMODEL is semi-distributed there is no difference in the computational effort, after calculation of the TWI, between a model run at a resolution of 1000 m or 1 m. As a result, various studies have examined the use of TOPMODEL at a range of resolutions [4-10], though to our knowledge only one paper has applied LiDAR-based elevation data with resolutions of ~2 m [11]. Much existing research into the resolution sensitivity of the TWI has been performed in order to understand the resolution sensitivity of TOPMODEL and has therefore focused only on the sensitivity of the (aspatial) distribution of the TWI, since this is the only TWI property used in TOPMODEL.

However, use of the TWI is not confined to TOPMODEL. For example, the TWI has been used as an index to indicate potential saturated and unsaturated areas in a catchment and predict the distribution of local soil moisture [12], [13], [14]. TWI is also used as input data to predict spatially varying evapotranspiration, liability to erosion or nutrient transport [15], [16] and in the automatic delineation/classification of landforms [17], [18], [19], since it represents an intuitive notion of wetness or proneness to generate surface flow.

Therefore this paper aims to not only analyse the resolution sensitivity of the TWI from a statistical point of view – as has been done in most TOPMODEL-related studies – but also to investigate the sensitivity of the spatial arrangement of the TWI.

2 Previous Research on Resolution Sensitivity

2.1 Gradient and Specific Catchment Area

Gradient and aspect are the magnitude and direction respectively of the 1st derivative of a continuous surface representing elevation [20]. The Specific Catchment Area (SCA) is defined as catchment area per unit contour length and is an important variable in hydrologic modelling [20], [21].

Of all terrain derivatives, gradient sensitivity to resolution has probably received the most attention within the GIScience community. For example, Vieux [22] explored the implications of smoothed and aggregated DEMs on gradient. A DEM with 30 m resolution was smoothed and downsampled to resolutions of 90 m, 150 m and 210 m using nearest neighbour interpolation. Vieux found that both smoothing and aggregation of the DEM reduced the spatial variability of both elevation and gradient values. For coarser resolutions lower mean and maximum gradient resulted.

Gao [23] derived gradient from DEMs with resolutions from 10 m to 60 m. For coarser resolutions steep gradients disappeared and intermediate gradient values became dominant. Thompson et al. [24] and Claessens et al. [25] looked at the resolution sensitivity of both gradient and SCA for DEMs with resolutions of between 10 m and 30 m. Again, both authors report lower values of gradient for coarser resolutions. Furthermore, Claessens et al. [25] show that the minimum values of SCA are higher with coarser DEM resolutions since they are directly linked to resolution by the division of the upslope area by contour length. The authors find “higher contribution of high specific catchment area values to the distribution” for coarser resolutions [25] and “lower values of $\ln(A_s)$ associated with the higher resolution DEM” [24] and thus underpin the study by Wilson et al. [26].

Garbrecht and Martz [27] examined various hydrological properties such as total channel length, drainage density and mean link drainage area. They found that for these properties, “the grid size dependency is introduced by the inability of a DEM to accurately reproduce drainage features that are at the same scale as the spatial resolution of the DEM” [27].

2.2 Topographic Wetness Index

The Topographic Wetness Index (TWI) is a compound terrain derivative. Kienzle [1] defines compound terrain derivatives as “terrain indices that combine two or more terrain attributes.” Other compound derivatives are for example total curvature (combines plan and profile curvature) and the stream power index.

Zhang and Montgomery [5] were among the first researchers who investigated the effects of different DEM resolutions on the TWI. They found that coarser DEM resolutions lead to a decrease in the mean gradient and an increase in the (D8-based) mean SCA. They suggest the latter occurs simply because with lower resolution minimum SCA (the area of a single raster cell) increases. In general, higher resolutions lead to lower TWI values. They consider the implications of lower resolution on the spatial distribution of the TWI to be particularly important, since many details of the river network as well as of the drier slopes disappear. However, they suggest that for resolutions of more than 10 m only a “marginal improvement in slope representation” occurs [5], although the real resolution of these data were probably less than the nominal resolution (c.f. §2.4).

Bruneau et al. [6] observed a change in the shape of TWI statistical distributions that may affect model runs within TOPMODEL. “This non-linear effect of space resolution may be due to differing effects on the two variables [gradient, SCA] used in determining the topographic index” [6]. This change in the shape of the TWI distribution was also reported by Saulnier et al. [8]. Kienzle [1] points out that in comparative studies between several catchments the reported resolution sensitivity of the TWI has to be taken into account. Finally, Wolock and Price [4] reported that the spatial pattern of the TWI is, unsurprisingly, much more complex for finer resolutions than it is for coarse ones.

2.3 TWI and High Resolution LiDAR Data

Lane et al. [11] computed TWI from, and used TOPMODEL with, high resolution (2 m) LiDAR data. In model runs they found saturated areas in the catchment that were not connected with the stream network because of low values of TWI in intermediate locations which persist even after large amounts of precipitation. At lower resolutions the number of these areas diminishes and the pattern of saturated areas becomes more coherent. Lane et al. [11] did not focus on TWI distribution but instead designed a TOPMODEL alternative, called the network-index approach, to overcome the shortcomings mentioned.

2.4 Nominal and Real Resolution

In the context of research on the sensitivity of terrain derivatives to the resolution of elevation data sets the term ‘resolution’ needs to be carefully defined. “The spacing of the original data used to construct a DEM effectively limits the resolution of the DEM. Decreasing the size beyond the resolution of the original survey data does not increase the accuracy of the land surface representation of the DEM and potentially introduces interpolation errors” [5]. Thus, elevation data in the form of a raster have both a nominal and a real resolution. The former can be stated explicitly as the size of the raster cells. The latter can be thought of as the minimum appropriate resolution as defined by Zhang and Montgomery [5]. In assessing the sensitivity of terrain derivatives to resolution, it is important to be clear as to whether the resolution in question is nominal or real. For example, Kienzle [1] showed that gradient and TWI exhibited greater sensitivity when derived from a DEM with finer real resolution.

In previous research on the sensitivity of the TWI and TOPMODEL to resolution a wide range of nominal resolutions have been derived from varying source datasets using a variety of interpolation methods (Table 1).

Table 1. Data source characteristics in resolution sensitivity studies of TWI/TOPMODEL. Source abbreviations: CMx: Contour map with x m elevation distance, AP: Aerial photogrammetry, DEM: Digital elevation model with x m (or x": x arcseconds) resolution.

Study	Source scale	Source	Resolutions	Notes
Wolock, Price [4]	(1:24'000)	DEM30	30 m, 90 m	Other resolutions than 30 m derived by bilinear resampling
	(1:250'000)	DEM3"	90 m	
Zhang, Montgomery [5]	1:4'800	CM6	2-90 m	
	“low altitude”	AP		~1pt/100m^2
Bruneau et al. [6]	1:10'000	CM	20-100 m	
Franchini et al. [7]	n. a.	DEM60	60-480 m	
Saulnier et al. [8]	1:25'000	CM10	20-120 m	Other resolutions than 20 m derived by subsampling 20 m DEM without aggregation
Brasington, Richards [9]	1:5'000	CM10	20-500 m	
Higy, Musy [10]	(1:25'000)	DEM25	25-300 m	Other resolutions than 25 m derived by resampling the 25 m DEM
Lane et al. [11]	n. a.	LiDAR	2-64 m	
Kienzle [1]	1:60'000	AP	5-100 m	Points at 100 m intervals and surface specific points (⅓ to ⅔ of all points), 103-850pts/km^2
	n. a.	DEM10		

This study aims to investigate the resolution sensitivity of the TWI with data of very high nominal resolution. The data in this study are not derived from paper maps, contour line data or aerial photogrammetry (as is often the case with other studies), but are based on densely sampled LiDAR ground data, so that at all of the resolutions analysed the real resolution of the data is higher than the nominal resolution of the DEM. In the remainder of this paper, we use the term ‘resolution’ to refer to nominal resolution.

Specific questions for investigation within this study can be set out as follows:

- How do the spatial patterns of SCA, gradient and TWI distribution vary with resolution?
- How do the statistical TWI distributions vary at different resolutions?
- What conclusions can be inferred for the use of the TWI within the TOPMODEL framework and other domains?

The following section gives an overview of the methodology applied. This is followed by an analysis of the influence of the digital elevation model (DEM) resolution on the spatial pattern of SCA, gradient and TWI before the statistical properties of these terrain derivatives are discussed and a set of implications for applications and other research are set out.

3. Methodology

The study area lies in the region of Boltigen north of the Swiss Alps, west of Interlaken. The mountainous catchment of the Wueestenbach river used in the TWI investigation is approximately 11 km^2 and confined by steep slopes at the valley head, while in some parts of the catchment there are cliffs.

In order to answer the research questions posed, the following methodology was adopted. DEMs of resolutions of 2.5, 5, 10, 20 and 40 m were independently generated from filtered ground LiDAR data (~0.7 points/m^2). IDW (Inverse Distance Weighting) with a weighting exponent of 2 was used as interpolator. The number of points used in interpolation was chosen such that – statistically – all points used in the interpolation lay within the cell being interpolated (Table 2).

Table 2. IDW interpolation parameters

DEM resolution	Number of points	Maximum distance threshold
2.5 m	5	10 m
5 m	20	10 m
10 m	70	20 m
20 m	280	40 m
40 m	1’120	80 m

Subsequently, the TWI was calculated using ArcGIS [28] and SAGA GIS [29]. The computation included a fill operation and the use of a multiple flow direction algorithm (MFD) according to Quinn et al. [30], [31]. This approach was recommended by Beven [2]. Multiple flow direction algorithms can account for divergent (sheet) flow, while single flow direction algorithms, e.g. D8, model only convergent flow often resulting in a multitude of parallel stream lines on hill slopes (cf. Fig. 1). The

MFD gives the catchment or upslope area of each point in the watershed. The catchment area per unit contour length was derived from this by applying a division by contour length. Contour lengths were computed l = 0.427 · resolution, where 0.427 is the mean of contour length for diagonal and cardinal neighbours [30], [31]. Gradient was computed by fitting a 2nd degree polynomial [32]. Because any method of calculating slope using eight neighbouring cells will tend to smooth gradients an additional form of gradient was calculated for the finest and the coarsest resolution called Weighted Downslope Gradient (WDG). In this calculation only lower neighbouring cells are considered. The gradient to each downslope neighbour is weighted according to:

$$w_i = \tan \beta_i / \sum_i \tan \beta_i \ . \tag{2}$$

A minimum value of 0.001 was imposed on the subsequently calculated tangent of the gradient to avoid division by zero.

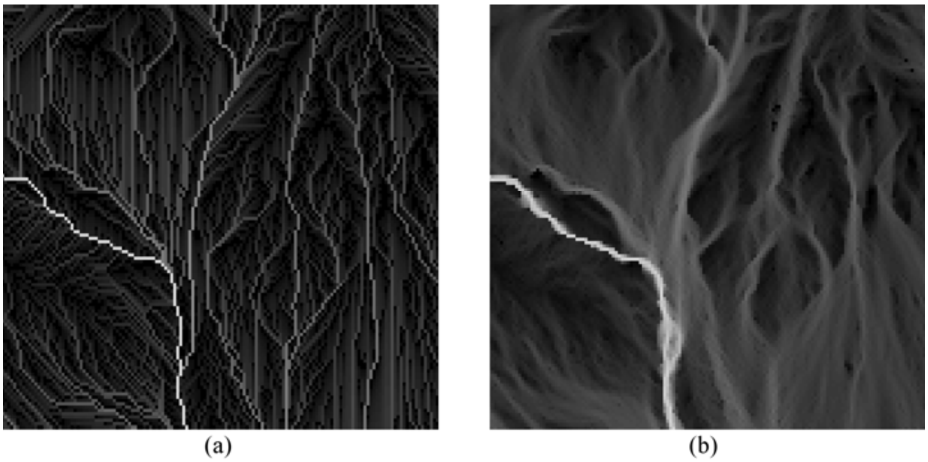


Fig. 1. Flow accumulation based on flow directions by (a) D8 and by (b) MFD

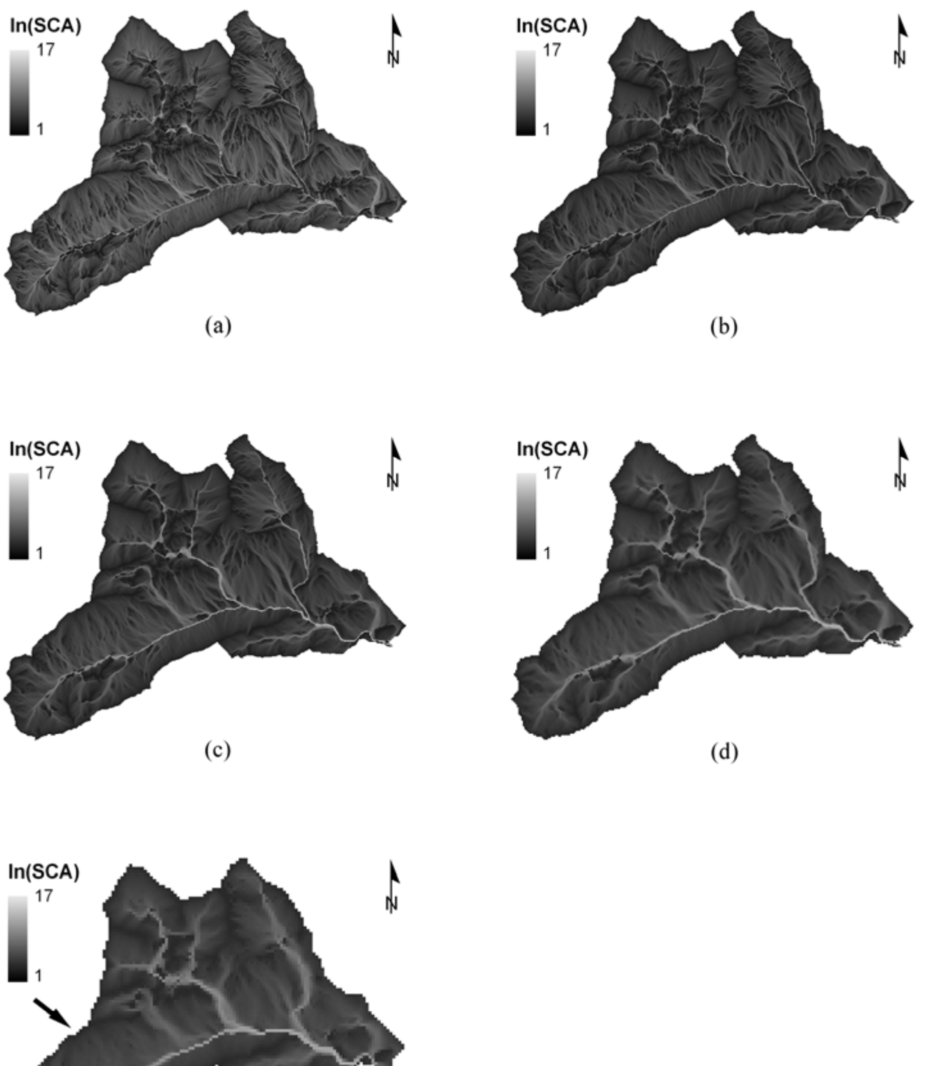
4 Results and Discussion

4.1 Spatial Distribution

Specific Catchment Area. All resolutions of SCA (Fig. 2) exhibit a sensible pattern with a clear stream network and flow accumulated downslope thanks to the fill operation that was carried out on the DEM in advance.

For relatively fine resolutions (below 5 or 10 m) the pattern of SCA is quite complex. Even small channels and rills are represented forming a dendritical network of high SCA values especially on longer slopes (cf. location of arrow in Fig. 2e).

The coarsening of the DEM resolution results in a loss of these fine details and higher SCA values are found only in medium-sized and large valleys. Smaller channels on hill slopes that are clearly depicted at finer resolutions become blurred. This can be seen in Fig. 3 which contains close-up views of the area highlighted by the arrow in Fig. 2e. SCA with 2.5 m resolution shows relatively homogenously distributed flow on the shoulder of the hill slope (upper left part of the depicted area). The surface flow than enters a very steep area of cliffs with very high gradients. Flow converges and is concentrated in rills and creases. Beneath the cliffs the hill slope once more becomes uniform and the water is dispersed over the entire area. This chain of processes is still, to some extent, visible in the SCA representation with 10 m but at 40 m the small scale morphometry of the terrain is completely lost and the cliffs are represented as a relatively uniform area of high gradient values. Thus the SCA does not represent channelled flow in the middle of the hill slopes and does not reach high values with respect to the background.



(a) (b) (c) (d) (e)

Fig. 2. Logarithm of Specific Catchment Area at (a) 2.5 m, (b) 5 m, (c) 10 m, (d) 20 m and (e) 40 m resolution

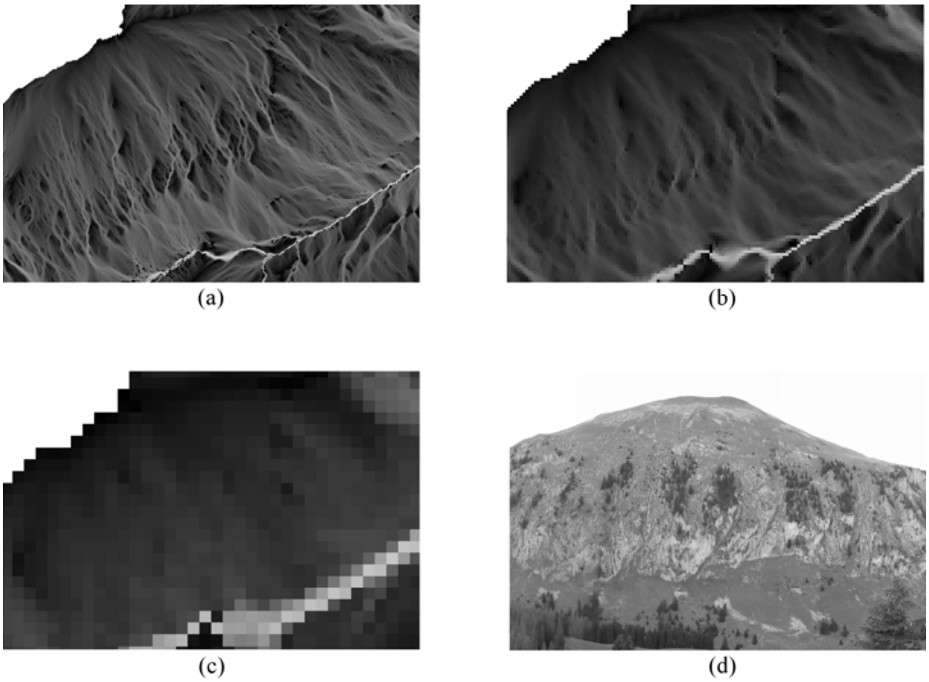
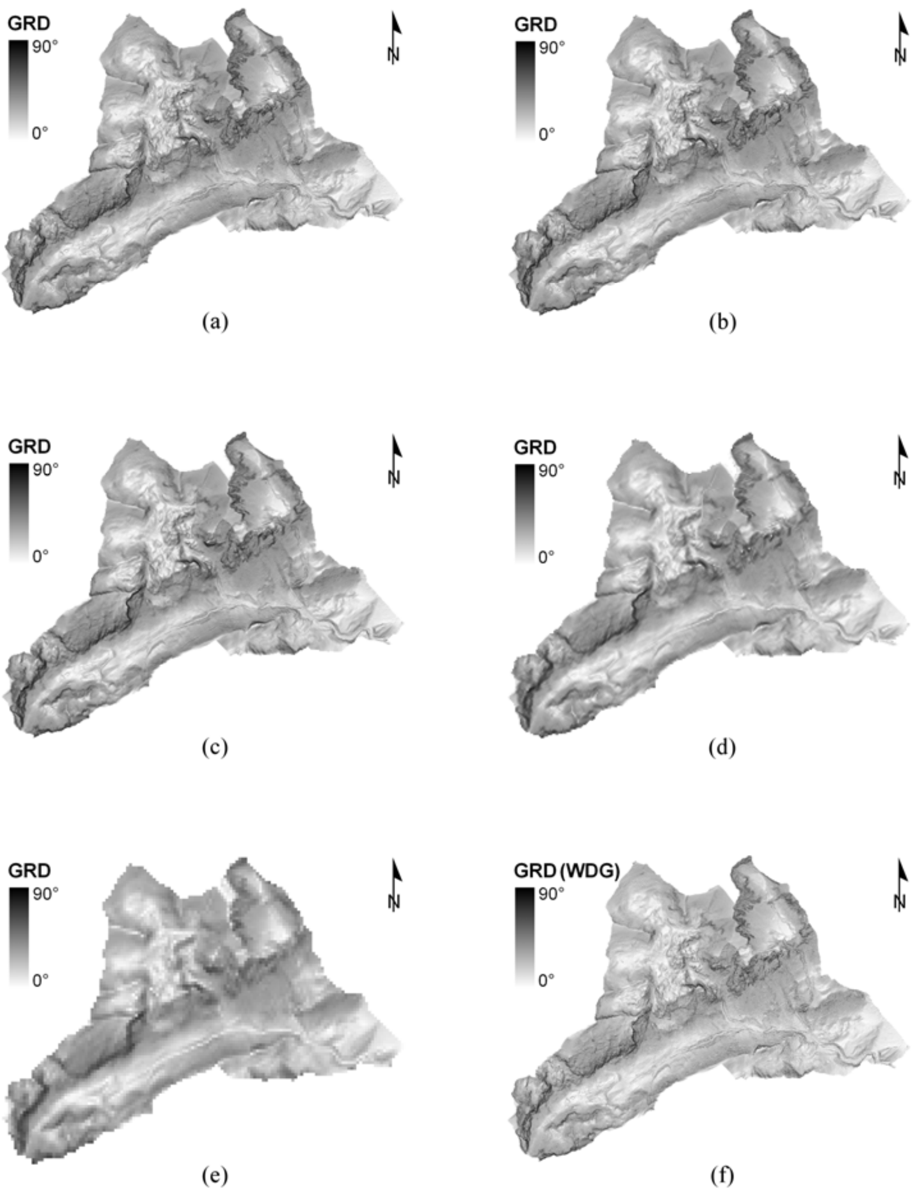

(a) (b) (c) (d)

Fig. 3. Close-up view of Specific Catchment Area at (a) 2.5 m, (b) 10 m and (c) 40 m resolution; (d) photograph of the situation. The location of the depicted area is indicated by an arrow in Fig. 2e.

Gradient. The spatial pattern of gradient is shown in Fig. 4a-e. High gradient values predominantly occur on the hill slope north of the main valley that runs along the southern catchment boundary. These regions of high gradient are indeed very steep slopes with outcropping cliffs with near vertical surfaces. North of these and at higher levels there are areas with low gradient values. The overall geomorphology is adequately represented at all resolutions. Finer resolutions differ in the geomorphologic detail they exhibit and in the values of gradient that occur. The first assertion rises from the inspection of the hill slopes. These are to a certain level still properly depicted at coarser resolutions. With finer resolutions, however, more detailed features, for example, debris fans beneath cliffs are also represented. These features that are omitted at coarser resolutions result in locally very high gradient values in an already relatively steep environment.

Fig. 4f shows the gradient approximated with the WDG method as described in §3. The spatial pattern of this gradient is noisier and depressions are wider as a result of the consideration of only the downslope neighbours of a cell.



(a) (b) (c) (d) (e) (f)

Fig. 4. Gradient at (a) 2.5 m, (b) 5 m, (c) 10 m, (d) 20 m and (e) 40 m resolution; (f) gradient at 2.5 m resolution according to WDG method

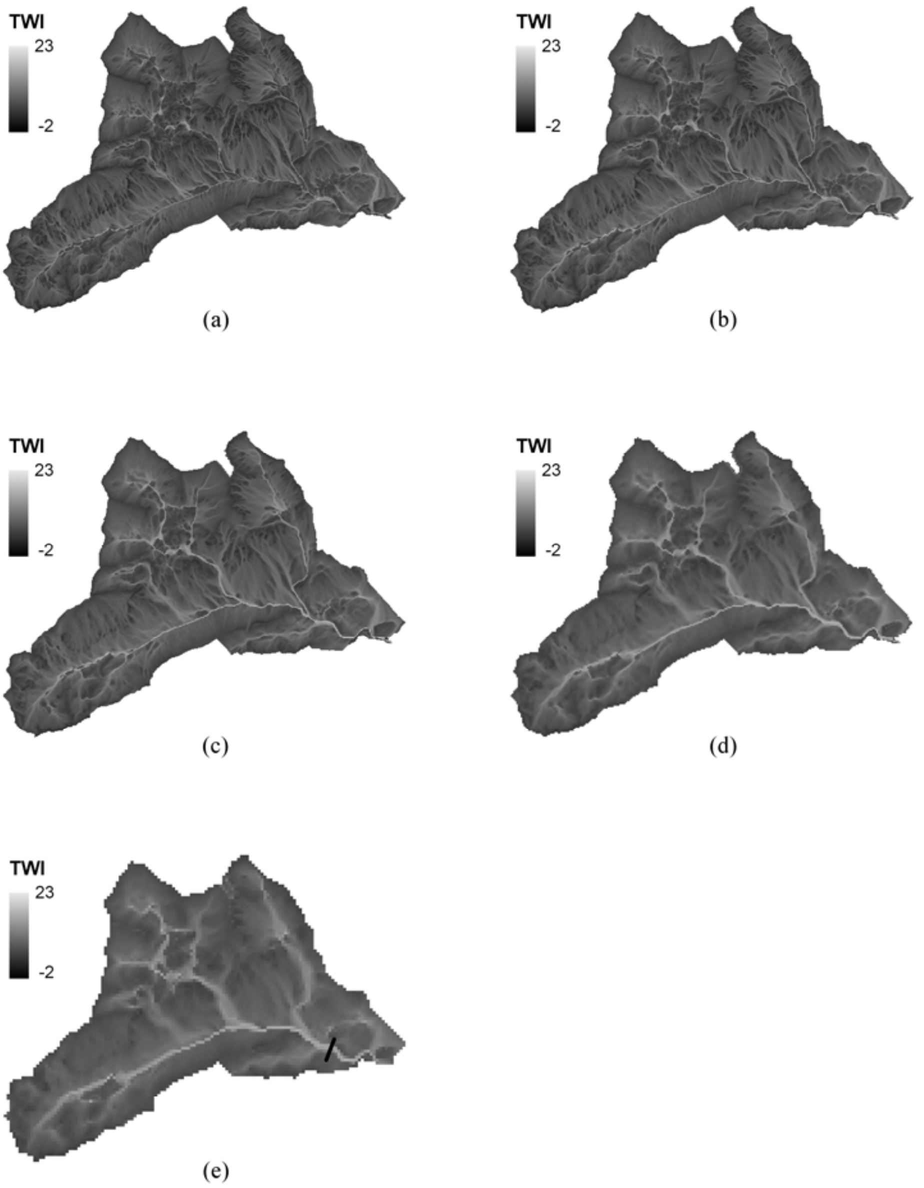
TWI. The spatial pattern of the resulting TWI at different resolutions is depicted in Fig. 5. Comparing the TWI rasters with the SCA and gradient rasters reveals a dominance of the hydrological over the morphometric property. The TWI essentially forms a network of high values that closely resembles the SCA pattern. For fine resolutions again the fine creases and rills on the hill slopes can be distinguished in the TWI rasters. High TWI values in the valley bottoms are very strongly concentrated in channels of a width of one or more cells. Low gradient values next to these channels cannot compensate for low SCA values, hence the relatively strong contrast of TWI channel values with the environment.

The reduction of detail in the process of lowering resolution is striking. This can be best seen from the perspective views in Fig. 6. In Fig. 6a hill slopes and the valley bottom are represented with very fine details. A path can be distinguished that runs across the hill slope in the foreground. Paths and roads are anthropogenic features that can significantly influence overland flow paths and as such their presence may be desired in input data for hydrological modeling. Approaches have been developed to retroactively incorporate such anthropogenic features in order to obtain more realistic overland flow paths [33], [34]. As can be seen from Fig. 6a the use of high resolution LiDAR data may allow such features to be directly modelled.

On the slopes on both sides of the valley small bumps (terrain undulations, debris) can be observed. The valley bottom is very complex. The main channel that drains through it is narrow, with in some parts side channels joining it. Most of these channels are one or several cells (i.e. slightly over 2.5 m) wide.

The complexity of the terrain diminishes in the representations with 10 m and 40 m resolution. Initially distinct features, for example the mound in the valley bottom (dark feature left of the centre of Fig. 6b) are still observed though finer details such as the unevenness of the hill slopes or the path are omitted. In general, the valley bottom is more level at coarser resolutions (cf. Fig. 7), and through the use of MFD (instead of D8) more prone to wider streams. Inflows from the slopes that were narrow channels at the finest resolution are now relatively broad branches of the stream network (at least 40 m, but also wider). The cliffs in the background are not so rugged anymore. It is important to note that the change in resolution does not only cause an increase in channel width as a function of resolution, but also because lower resolutions result in less differentiated flow and thus wider channels where flow concentrates.

Fig. 7 also illustrates that some hill slopes may be adequately represented with different resolutions. While the slope on the right (South) experiences barely any degradation with coarser resolutions, the opposite side shows relatively pronounced differences at differing resolutions. The hill slope on the right has itself a coarser scale than the one on the left.



(a) (b) (c) (d) (e)

Fig. 5. TWI at (a) 2.5 m, (b) 5 m, (c) 10 m, (d) 20 m and (e) 40 m resolution. The black line in (e) indicates the location of the profiles in Fig. 7.

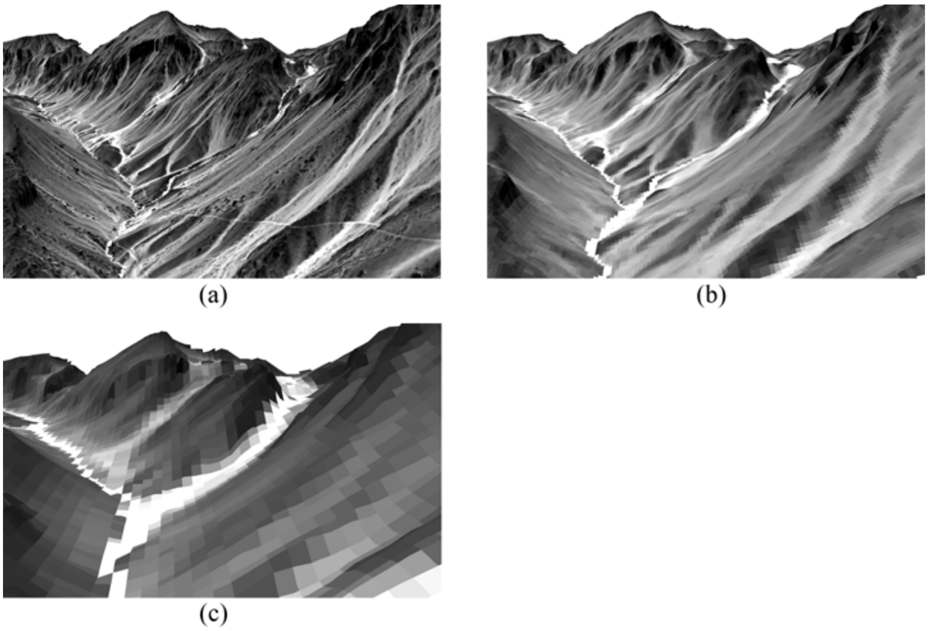


Fig. 6. Perspective view of TWI at (a) 2.5 m, (b) 10 m and (c) 40 m resolution

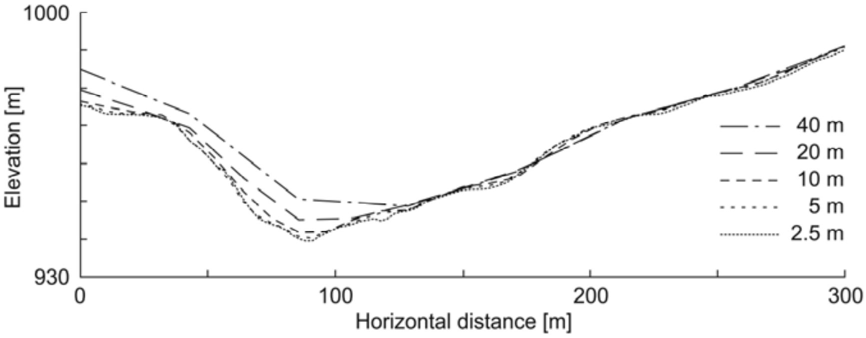


Fig. 7. Elevation profiles across a channel in the valley bottom

4.2 Statistical Distribution

Table 3 shows the statistical properties of the SCA distribution. Minimum and maximum SCA values converge with coarsening resolution. Minimum catchment area values and hence SCA values are determined by the DEM resolution as Claessens et al. [25] pointed out. The former is simply resolution squared, while the latter undergoes a division by contour length which is in turn determined by the resolution and some coefficient (constant across all resolutions). Division by contour length also affects maximum SCA values. One single cell at the catchment outlet that receives all water (i.e. has a catchment area equal to the total catchment area) with a width of 1 m will automatically obtain a SCA value that is ten times higher than a cell with a width of 10 m. This effect influences all SCA values and is reflected by mean SCA value decreasing for coarser resolutions. At the same time the median, which is insensitive to extremes, and the quartile values increase. This reflects the shift in the obtainable minimum SCA values. In summary, in the upper parts of the catchment SCA of a coarse resolution has higher values than SCA of finer resolutions, while in the lower parts of the catchment the situation is inverted.

Table 3. Statistics for Specific Catchment Area

	Specific Catchment Area [m]				
Resolution	Minimum	Maximum	Mean	Stddev	Median
2.5 m	5.85	10'022'410	8'786.05	172'457.16	238.56
5 m	11.71	4'996'783	8'683.48	126'308.21	309.34
10 m	23.42	2'491'526	8'358.53	88'702.11	389.52
20 m	46.84	1'232'313	7'893.18	59'461.81	492.10
40 m	93.68	578'091	7'009.97	37'561.27	625.69

Gradient also experiences a shift when resolution is changed as Table 4 shows. As expected, maximum and mean values of gradient are lower for coarser resolutions. All minimum values are 0° except the one at resolutions of 40 m.

Table 4. Statistics for gradient

	Gradient [°]				
Resolution	Minimum	Maximum	Mean	Stddev	Median
2.5 m	0	88.37	30.34	13.91	29.98
5 m	0	86.67	30.17	13.29	30.12
10 m	0	83.42	29.89	12.88	30.06
20 m	0	77.71	29.30	12.56	29.70
40 m	0.07	69.96	28.53	12.20	29.09
2.5 m WDG	0	88.48	25.48	13.09	24.34
40 m WDG	0	68.16	23.40	11.08	23.41

The changes in the distribution of the SCA and gradient are reflected in the TWI, which is calculated according to equation (1).

Table 4 also illustrates the statistical properties of gradient calculated using WDG. As can be seen the ranges of values are almost identical to the gradients calculated with a 2nd order polynomial of the same resolution. However, the peak of the distributions has shifted to lower values and hence the distributions are more right skewed. This affects the mean gradient value by approximately 5°.

As can be seen from Fig. 8 the TWI distributions of different resolutions differ visually, and these differences have been shown by Mann-Whitney U tests to be statistically significant. For coarser resolutions the shift to higher TWI values results in an increase of mean and median values with an increase in mean from 5.13 to 6.5 and median from 5.1 to 6.16.

Additionally, there is a change in the shape of the TWI distribution, as Bruneau et al. [6] and Saulnier et al. [8] observed for resolutions between 20 m and 100 m and between 20 m and 120 m, respectively.

For resolutions of 40 m relatively high TWI values dominate though, maximum values are nevertheless lower for coarser resolutions (Table 5). On the other hand the minimum TWI value is lower for finer resolutions. Both these effects seem to be (at least partially) caused by the behaviour of the SCA minimum and maximum values for changing resolution. The influence of gradient on the behaviour of the TWI is such, that lower gradient values for coarser resolutions generally foster higher TWI values for these resolutions.

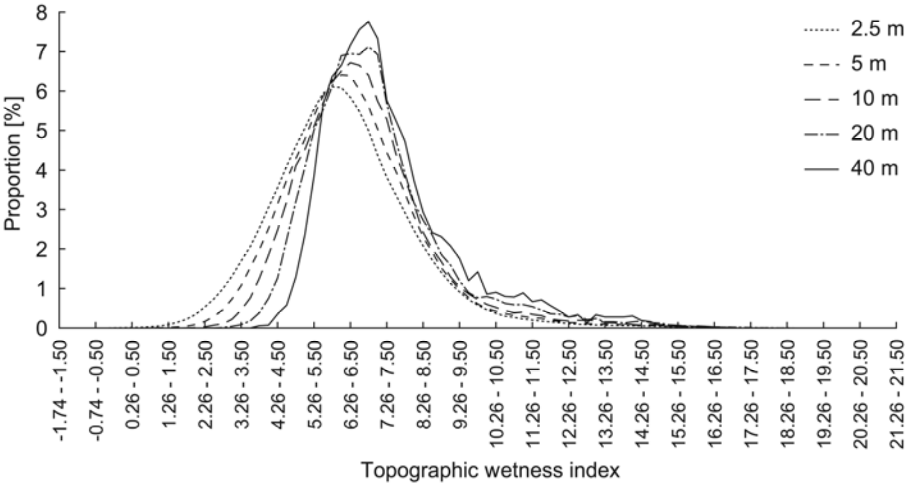


Fig. 8. Distributions of the TWI at different resolutions

Table 5. Statistics for TWI

	TWI						
Resolution	Minimum	Maximum	Mean	Stddev	Median	Skewness	Kurtosis
2.5 m	-1.56	22.68	6.19	1.94	6.05	0.91	2.86
5 m	-0.31	19.87	6.47	1.88	6.29	1.14	3.31
10 m	1.49	18.05	6.75	1.86	6.53	1.32	3.42
20 m	2.59	16.82	7.06	1.86	6.76	1.42	2.99
40 m	3.75	16.03	7.42	1.84	6.98	1.40	2.28
2.5 m WDG	-1.80	23.02	6.43	2.01	6.30	0.95	3.48
40 m WDG	3.79	18.38	7.69	1.97	7.27	1.43	2.72

Table 5 also shows that the differences in gradient shown in Table 4 for different algorithms have little influence on TWI, again demonstrating the predominant influence of SCA.

Surprisingly, in the present study TWI has negative minimum values for the resolutions of 2.5 and 5 m (-1.56 and -0.31, respectively). The minimum TWI value for 10 m resolution is positive (1.49).

To the authors' knowledge no occurrence of negative values is reported in the existing literature about the TWI. Two factors interact to allow the occurrence of such values: small specific catchment areas and high gradient values. Both these factors are more probable in DEMs of (very) fine resolution. As mentioned in the introductory section, most existing studies have investigated the behaviour of the TWI for DEMs of nominal resolutions down to 10 m. It is hence supposed the nominal (or the real resolution) of the DEMs used in these studies was too coarse for negative TWI values to occur and/or the topographies of the study areas were less pronounced than in the present study. Holko and Lepistö [35] did indeed apply TOPMODEL to a mountainous catchment with a mean gradient similar to this study, but they used a DEM of 100 m nominal resolution derived from a map of scale 1:10'000. Thus it is assumed that no negative TWI values resulted in their study. They do not state the TWI distribution explicitly.

Cells of a certain gradient with only a small area draining to them are prone to negative TWI values. A negative TWI value results when:

$$\ln\left(A_s/\tan\beta\right)<0. \quad \Leftrightarrow \quad A_s < \tan\beta. \quad \Leftrightarrow \quad \arctan A_s < \beta. \tag{3}$$

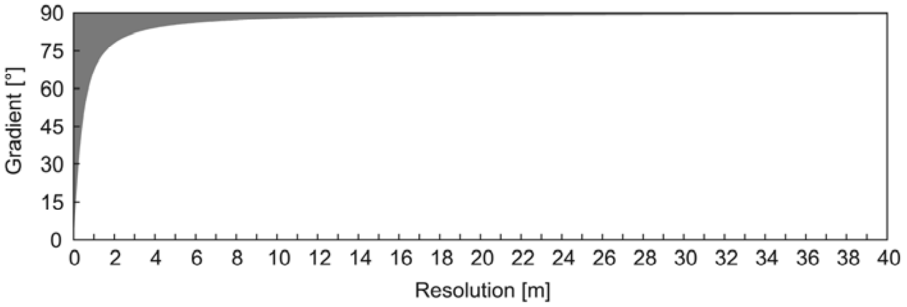


Fig. 9. Critical values of gradient for negative TWI values. Data that lie inside the gray area result in negative TWI values.

Fig. 9 shows the critical gradient that lets $\ln\left(A_s/\tan\beta\right)=0$ if A_s equals one grid cell, in relation to the DEM resolution used. Thus for a DEM of 1 m resolution a gradient value of 67° and for a DEM of 0.5 m resolution 50° would allow negative values to occur. Resolutions of this order of magnitude are well within the realm of the current generation of LiDAR.

5 Conclusions

In this study we sought to explore the influence of resolution on a compound topographic index, the Topographic Wetness Index (TWI), derived from the Specific Catchment Area (SCA) and gradient. Our study used raw LiDAR data to derive elevation models of a variety of resolutions using a simple interpolation method (IDW) and aimed to examine the dependency of TWI and its constituents on resolution. Such work is important, since as LiDAR data proliferates the assumption that higher resolution is *de facto* better for modelling is proliferating. Furthermore, previous studies of the implications of changes in resolution on TWI have used data with a *real* resolution (that is, the resolution of features likely to be resolved in the data) considerably less than the *nominal* resolution (the resolution reported for the data, independent of its derivation). This is the first key conclusion of our work, which stems from an examination of previous sensitivity tests – authors should report both *nominal* and *real* resolutions.

Changing resolution influences the derived TWI in several ways. Lowering resolution affects both spatial and statistical distributions of gradient and SCA. From a spatial point of view the loss of detail that occurs between resolutions of 2.5 and 40 m is striking. Detailed terrain features, such as rills, rocks and debris are omitted resulting in a shift in gradient values and hence TWI. Moreover, minor topographic elements in valley bottoms become blurred leading to flow path ambiguity and channel widening beyond that resulting from changes in minimum cell width alone. Furthermore, the degree of loss of detail is related to the scale at which features in the landscape manifest themselves. This effect was well illustrated by a valley profile where small scale features dominated on one hill slope (suggesting a need for higher resolution data), whilst the opposing hill slope was well captured at all resolutions. These effects only became visible at higher resolutions, and reinforce the importance of multi-scale analyses, based on data with a high real resolution, similar to those carried out by Wood [36].

The distribution of the TWI at all resolutions was strongly dependent on the SCA, reflecting the importance of the choice of flow algorithm applied. The location of the highest TWI values remained similar for all resolutions. However, the distribution of the medium and low values is affected, primarily on relatively long hill slopes where at different resolutions quite distinct TWI patterns develop.

From an aspatial, statistical viewpoint there are some pronounced differences between resolutions. Previous research on gradient, SCA and TWI sensitivity has been confirmed and underpinned with data whose real resolution is always higher than the nominal resolution at which the calculations are carried out. Additionally, comparison of TWI values derived from a 2nd degree polynomial and from an additional approach (Weighted Downslope Gradient) showed that although gradient values were sensitive to algorithm, their influence on TWI was limited.

The behaviour of the SCA at different resolutions was primarily controlled by flow width or contour length and hence resolution. This control leads to lower minimum and higher maximum values for DEMs at fine resolutions. The behaviour of gradient and especially SCA are reflected in the resolution sensitivity of the TWI. The TWI distribution exhibits a shift to higher values for coarser resolutions and changes in the shape of the distribution. This may lead to differences in the performance of TOPMODEL (cf. [37]). Specifically, coarser resolutions with lower mean TWI values exhibit less subsurface flow and a smaller saturation deficit and thus tend to produce larger saturated areas and more surface runoff. However, approaches to deal with TWI resolution sensitivity within TOPMODEL through the use of scaling factors have been developed (cf. [7], [8]).

However, when TWI and/or TOPMODEL are used to make spatial assertions, TWI resolution sensitivity gives rise to new problems. As was seen in the results section, the spatial patterns of the TWI and hence derived patterns of saturated and unsaturated areas, evapotranspiration, liability to erosion or nutrient transport vary between different resolutions. More generally, TWI resolution sensitivity needs to be taken into account when working with thresholds, for example in the field of landscape classification, or when doing comparative studies in a data-driven situation, when at different locations DEMs of different resolutions are available.

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