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The use of LIDAR as a data source for digital elevation models – a study of the relationship between the accuracy of digital elevation models and topographical attributes in northern peatlands

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Abstract

It is important to study the factors affecting estimates of wetness since wetness is crucial in climate change studies. The availability of digital elevation models (DEMs) generated with high resolution data is increasing, and their use is expanding. LIDAR earth elevation data have been used to create several DEMs with different resolutions, using various interpolation parameters, in order to compare the models with collected surface data. The aim is to study the accuracy of DEMs in relation to topographical attributes such as slope and drainage area, which are normally used to estimate the wetness in terms of topographic wetness indices. Evaluation points were chosen from the high-resolution LIDAR dataset at a maximum distance of 10 mm from the cell center for each DEM resolution studied, 0.5, 1, 5, 10, 30 and 90 m. The interpolation method used was inverse distance weighting method with four search radii: 1, 2, 5 and 10 m. The DEM was evaluated using a quantile-quantile test and the normalized median absolute deviation. The accuracy of the estimated elevation for different slopes was tested using the DEM with 0.5 m resolution. Drainage areas were investigated at three resolutions, with coinciding evaluation points. The ability of the model to generate the drainage area at each resolution was obtained by pairwise comparison of three data subsets.

The results show that the accuracy of the elevations obtained with the DEM model are the same for different resolutions, but vary with search radius. The accuracy of the values (NMAD of errors) varies from 29.7 mm to 88.9 mm, being higher for flatter areas. It was also found that the accuracy of the drainage area is highly dependent on DEM resolution. Coarse resolution yielded larger estimates of the drainage area but lower slope values. This may lead to overestimation of wetness values when using a coarse resolution DEM.

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1 Introduction

The most recent scientific assessment of climate change by the Intergovernmental Panel on Climate Change states that the world is becoming warmer, and that the extent of warming will be greater at higher latitudes (Denman et al., 2007). Northern peatlands store about 25 % of the world's terrestrial carbon and emit between 10 and 20 % of its natural methane sources (Gorham, 1991, 1995; Moore et al., 1998). Estimating the distribution of wetness in peatlands is thus essential in order to determine their influence on the emission of greenhouse gases. Estimating the distributed wetness is one part of the effort to develop and explore innovative methods that can help us understand the relations between the physical attributes of peatland surface topography, permafrost, and hydrology, and the corresponding plant communities and their carbon storage.

A topographic wetness index (TWI) can be calculated using estimates of the slope and drainage area. Wetness is a geographical phenomenon that varies continuously over space. An important characteristic of peatlands is that the change in elevation between neighboring points is relatively small, while the difference in wetness is relatively large. The use of high resolution data to estimate the wetness at many points over an area may thus provide a tool for the calculation of gas emissions in peatlands.

In order to initiate a study on the hydrology of peatlands, and at a later stage detect the important changes in wetness, it is necessary to create a digital elevation model (DEM) for a specific peatland area. In this study, high resolution LIDAR data (Fowler, 2001) were used to generate a DEM for use in the estimation of wetness in a peatland area in northern Sweden.

2 Research questions and hypotheses

Bases on the introduction presented above, the following research questions were formulated.

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1. Which parameters are important for the accuracy of a digital elevation model created using a standard interpolation method for a peatland area?
2. Does the accuracy of the DEM change with the slope of the terrain and, if it does, to what extent?
3. To what extent do the estimates of the slope and drainage area vary with the resolution of the digital elevation model?

We hypothesize that: DEMs are sensitive to different interpolation parameters; the accuracy of the DEM is different for different gradients; and that the estimated slopes and drainage areas are dependent on the resolution of the model.

3 Objectives and aims

The main objective of this study was to investigate the variation in the accuracy of elevation using high resolution LIDAR data for the generation of a DEM for northern peatlands. The results, which will probably be highly correlated to interpolation parameters and scale, will give an indication of the potential of LIDAR data and DEMs for hydrological modeling in peatlands. The primary objective was to investigate the role of interpolation parameters in the generation of the DEM. The secondary objective was to determine the accuracy of the DEM for different terrain with different slopes, and to investigate how the estimates of the slope and drainage area differed with different model resolution. The scale problem, i.e. the spatial resolution of the DEM, will be discussed for both objectives.

In order to fulfill the objectives a number of specific aims were defined:

1. To create a DEM for the peatland area, using a standard interpolation algorithm with different spatial resolutions and search radiuses.
2. To evaluate the accuracy in the prediction of the elevation using the DEM with high accuracy data.

3. To calculate the accuracy in the DEM estimates of elevation for different slopes.
4. To study how the estimated slope varies with DEM resolution.
5. To study how the estimated drainage area varies with DEM resolution.

4 Materials and methods

4.1 Elevation data and study site

This study is based on earth surface elevation data measured at the Stordalen mire and its catchment area. Stordalen is a peatland area in the Arctic region of Abisko in northern Sweden. The hydrology and soil moisture conditions of the Stordalen mire have been reported previously (Rydén et al., 1980). Apart from studies associated with the well-known International Biological Program (IBP), (Sonesson et al., 1980), the Abisko area has been included in many research programs, and it climatological records extend from 1913 to the present date (Andersson et al., 1996). This site is thus suitable for investigating methods of estimating changes in carbon storage, providing the possibility of validating tools for the prediction of changes in peatlands with past and future changes in permafrost. An area of approximately 16 km^2, containing the Stordalen mire, was selected as the study area in this project.

An airborne LIDAR device has been used to measure the surface elevation. LIDAR is an acronym for "LIght Detection And Ranging", and is a laser-based, remote sensing system used to collect various kinds of environmental data, including topographic data (Fowler, 2001). In this study, the high resolution data points (the raw data) have an average spatial distribution of approximately 13 points m^{-2}. Over the area defined above the total number of measured elevation data points is 76 940 341.

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4.2 General process

The elevation data were used to generate a DEM. Figure 1 illustrates the general process applied for the generation of the DEM, as well as the evaluation of relationships between the accuracy of the DEM and different topographic attributes, using different resolutions and search radiuses. The general methodology used to investigate the influence of slope, and the possible relation between resolution and estimates of the slope and drainage area are also presented.

4.3 Selection of evaluation data points

Some of the raw LIDAR data have been selected and saved for the evaluation of different interpolation methods. These data were excluded from the interpolation process and the generation of the DEM. The criterion for selecting the evaluation points was that the distance between the cell center in the DEM and the selected point should be less than, or equal to, 10 mm. This enables us to validate the estimated elevations at the cell centers using data values that were measured at almost the same location (maximum 10 mm away from the point of interest).

A MatLab (MathWorks, 2008) program has been created to perform the selection process. All 76 940 341 data points were processed. The program calculates four distances from each point to the nearest four cell centers. All data points less than or 10 mm from the nearest cell center are then selected to be evaluation data points. The calculation of the nearest center points is dependent on the resolution (cell size) of the DEM. The following six resolutions were used: 0.5, 1.0, 5.0, 10, 30 and 90 m. This implies dividing the raw data into 12 subsets, six for interpolation and six for evaluation. The number of points for selected evaluation is presented in Table 1 below.

The minimum number of evaluation points was set at 60 according to the American Society for Photogrammetry and Remote Sensing (ASPRS, 2005). As can be seen from Table 1, the number of points less than or 10 mm from the nearest four cell centers for the resolutions 30 m and 90 m is less than 60. To obtain more points for evaluation

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at these resolutions the distance from the cell centers was increased to 30 mm (30 m resolution) and 50 mm (90 m resolution). We are aware that this modification may constitute a weakness in the methodology, and thus decided to use the original distance (10 mm) and the extended distances (30 and 50 mm) in the evaluation.

4.4 Generation of the digital elevation model

The spatial autocorrelation of the LIDAR data was tested by the generation and interpretation of semivariograms for three 225 m^2, randomly selected areas: one with steep terrain, one with an intermediate slope and one with flat terrain. The terrain was divided into these categories using a DEM with 0.5 m resolution (see Sect. 4.6). The data within the area were corrected for the influence of the major slope in the area, i.e. a mountainside. Semivariograms of each area were then created and interpreted. None of the areas showed significant spatial influence on a point further away than 3.7 m.

The DEM was created using the inverse distance weighting (IDW) interpolation technique (Shepard, 1968). This method is based on the assumption that an interpolated point is influenced more by nearby data points than points further away. The choice of this method, rather than more advanced interpolation algorithms such as bicubic spline and Kriging, is justified by the facts that it is a standard interpolation algorithm available in most statistical software packages, it is commonly used by non-experts, and no spatial autocorrelation was found in the dataset.

Six different DEMs were created. The resolutions used were 0.5, 1, 5, 10, 30 and 90 m. The value of the search radius was varied between four different values (1, 2, 5 and 10 m) for each resolution (cell size). The larger the search radius, the more data are obtained, but the risk of including outliers in the interpolation is increased. Too large a search radius will also include data that have no influence on the topography, as shown in the semivariogram analysis. The number of interpolations was thus 24 (six resolutions x four search radiuses).

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A program was developed in MatLab to control the interpolation process, including the problem of processing such a large number of elevation data points. In order to conduct the interpolation process for each cell it is necessary to search inside a relatively large database. Such a process can be very slow since it has a computational complexity of n2 (in our case 76 940 3412), and may take several weeks. In order to speed up the process, a spatial index key called a Morton value (Orenstein and Manola, 1988) was calculated for each data point. Adding the spatial index decreases the computational complexity to *nlogn*, making it is possible to deal with a large number of data points within a reasonable time.

4.5 DEM evaluation

The purpose of evaluating the DEM at different resolutions is to detect possible differences, and identify the resolution that represents the evaluation data most accurately. To do this, we calculated the deviations between the measured evaluation data points and the interpolated values for the cell center for all combinations of resolution and search radiuses.

The technique most appropriate for measuring the accuracy of the DEM depends on the kind of error distribution. A normal distribution of the errors is rare in a DEM derived from data collected by LIDAR, due to e.g. filtering and interpolation errors (Höhle and Höhle, 2009). The quantile-quantile plot test (the q-q test) was used to establish the degree of deviation of the data from a normal distribution. The quantiles of the errors (Δh) are plotted against the theoretical quantiles of a normal distribution. If the data distribution is normal, the q-q plot should yield a straight line. Figure 2 shows the result of the q-q plot for the 0.5 m resolution, where it can be seen that there is a strong deviation from a straight line, indicating that the data are not normally distributed at this resolution.

A non-normal error distribution suggested by (Höhle and Höhle, 2009) was therefore used. This requires the calculation of four parameters, namely the median, the normalized median absolute deviation (NMAD) and two sample quantiles.

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The distribution of the differences in elevation (Δh) and the absolute differences in elevation ($|\Delta h|$) were used as measures of the accuracy of the DEM. Absolute errors were used because we are interested in the magnitude of the errors, and not their sign. Using absolute values also excludes the assumption that the distribution is symmetric.

The measurement accuracy is determined by calculating sample quantiles of the absolute differences ($|\Delta h|$) (Höhle and Höhle, 2009). The sample quantiles is the order of the sample [$x1, \ldots, xn$], where $x(1)$ denotes the minimum and $x(n)$ the maximum value in the dataset. For example, the 50 % sample quantile of $|\Delta h|$ means that 50 % of the errors have a magnitude within the interval [0; $Q_{|\Delta|}(50)$]. The 50 % quantile is denoting as median. The median of the error is a robust measure, which provides an estimate of a systematic shift in the DEM moreover; the median is less sensitive to outliers in a dataset.

The NMAD is used as a measure of the standard deviation, but is more resilient to outliers in the dataset (see Eq. 1).

$$\mathrm{NMAD} = 1.4826 \cdot \mathrm{median}_j(|\Delta h_j - \mathrm{m}_{\Delta h}|) \tag{1}$$

where

Δh_j denotes the individual errors $j = 1, \ldots$, n and,

mΔh denotes the median of the differences in elevation.

4.6 Accuracy of the DEM for terrain with different slopes

In order to study the accuracy of the DEM in relation to the slope of the terrain the evaluation points were divided into six subsets, corresponding to six slope intervals. Slopes were calculated according to (Pilesjo et al., 2006). Slopes with gradients from 0 to 50 degrees were divided into five equal intervals, while the sixth interval consisted of slopes steeper than 50 degrees. A resolution of 0.5 m was used to estimate the slope. The 0.5 m resolution was chosen since this has the largest number of evaluation points. The evaluation points are divided into six equivalent datasets, and the accuracy of the DEM was calculated for all these datasets.

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4.7 Relationship between the slope and drainage area for different DEM resolutions

Three different DEM resolutions were used to investigate the relationship between the estimates of the slope and drainage area, (Pilesjo et al., 2006) on the one hand, and the DEM resolution on the other. Resolutions of 10, 30 and 90 m were used, due to the overlapping evaluation centre cell points for these resolutions (i.e. the center of a 90 m cell is also the center point of a 30 and 10 m cell). The slope and drainage area evaluation cells selected from the 10 and 30 m resolution DEMs are thus the ones that have the same cell centre position as the location of the 90 m resolution evaluation cells. This results in three subsets of data that have the same number of evaluation points with the same locations, but contain slope and drainage area values estimated using different DEM resolutions. The results obtained from the three subsets are then compared to identify/reveal possible differences in the estimated slopes and drainage areas. The differences between pairs of different resolutions were calculated.

5 Results

5.1 Evaluation of the DEM accuracy

Twenty four different DEMs, interpolated using six different resolutions (cell sizes) and 4 different interpolation search radiuses, for the same area, were to be evaluated. The next step is to determine which combination of resolution and search radius gives the best accuracy. Using the robust accuracy measures appropriate for non-normal error distributions, we calculated the median, the NMAD and two quantiles (68.3 % and 95 %) for each combination of resolution and search radius. The medians were all zero except for the median at 90 m resolution, which varied between −10 and −20 mm depending on the search radius. The results of the NMAD calculations are given in Table 2. The values indicate that the accuracy of the DEM is the same for different resolutions when using the same interpolation search radius. The accuracy is generally higher the shorter the interpolation search radius. The results for the two quantiles are presented in Table 3, and confirm the NMAD results. This is a logical result, as increasing the interpolation search radius can be expected to increase the errors in the DEM. According to the measures of accuracy, the six most accurate combinations of resolution and search radius are those with the 1 m interpolation search radius. For these six cases, the maximum errors in the elevations are around 40 mm within the 68.3 % quantile of the data (see Table 3). Moreover, the maximum errors in the DEM elevations are around 0.1 m within the 95 % quantile of the data.

5.2 Accuracy of the DEM for different slope intervals

The results of evaluating the relationships between the six different slope intervals and the errors represented by the NMAD are shown in Fig. 3. When visually analyzing the shape of the slope error curve it is obvious that there are larger errors in elevation when the terrain is steep than when it is flat. The first point in Fig. 3a shows that for slopes between 0 and 9.99 degrees the error in elevation is around 0.03 m. Figure 3b illustrates two different quantiles of errors, also confirming that errors are larger in areas with steeper slopes.

5.3 Slope estimation using different DEM resolutions

Evaluation of the slopes estimated with the DEM at different resolutions shows that the medians of the differences between the slopes have negative signs, i.e. lower resolution (larger cell size) generates lower values of the slope. The frequencies of the differences in the slopes are shown in Fig. 4, where the negative skewness of the distributions can also be seen. The NMAD and the quantile results also confirm the relationship between the values of the slope and the resolution. Results for the median, NMAD and the two quantiles are given in Table 4.

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5.4 Estimation of the drainage area using different DEM resolutions

The medians of the differences between drainage areas estimated using different resolutions have positive signs, i.e. the lower the resolution (the larger the cell size) the higher the values of the drainage area. The frequencies of the differences in drainage area are illustrated in Fig. 5, where the shift of the median towards positive values is clear. The NMAD and the quantile results also confirm the relationship between the values of the drainage areas and resolution. Results for the medians, NMAD and the two quantiles are given in Table 5.

6 Discussion

A number of choices influence the results of this study, some of which are discussed below. Regarding the interpolation algorithm, we chose the IDW algorithm, mainly because it is one of the most commonly used for interpolating scattered points. In order to determine whether there were large differences in the results when using other interpolation techniques, we created DEMs using the nearest-neighbors interpolation and the bilinear interpolation algorithm. However, the results showed the same trend in errors as the IDW. This confirms that the use of these other algorithms has only slight effects on the results. We also tested the possible spatial autocorrelation of the dataset in order to rule out the need for a geostatistical (Kriging) approach (Cressie, 1993).

Regarding the evaluation data, ground truth field data are normally used for the evaluation of interpolated DEMs. In this study, we excluded certain data points from the raw data, and then used them for evaluation purposes. The excluded evaluation data were taken at a maximum distance of 10 mm from the centers of the cells, and were not used in the interpolation process. In order to increase the number of evaluation points we increased the maximum distances for the 30 and 90 m cells to 30 and 50 mm, respectively, giving 230 and 68 points, instead of 57 points and 6 points, respectively. This is definitely a weakness of the methodology. However, the results obtained using

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the extended evaluation dataset show the same trend in errors as evaluation of the limited number, confirming that the use of the modified selection criteria did not affect the results significantly. The extended selection was justified for statistical reasons.

When choosing the different resolutions of the DEM, we logically assumed that a high resolution should reflect reality better than a poor resolution. However, it is still interesting to create and test a DEM with different resolutions since, in most cases, DEMs with poor resolutions are more commonly available, and thus more frequently used. Evaluation of the accuracy for different resolutions showed approximately the same results regarding elevation. This was expected, since the evaluation points are all located close to, or very close to, the cell centers. The interpolation algorithm can then be expected to work equally well for all resolutions. However, the uncertainty between the evaluation points, in this case the centers of the cells, will be much higher at lower resolutions, where the distances between the centers of the cells are greater.

Employing different search radiuses changes the number of data points included in the interpolation for each cell. The reason for varying the search radius in this study was that available DEMs with the same resolution are often created from different sources, having different numbers of known data points. We expected that the use of different resolutions and search radiuses would have considerable effects on the results, such that the estimate of a point close to a large number of known data points would be better than that for one far away from the data points. This was shown by the autocorrelation study and the search radius study. The increase in search radius did not give a better result since the spatial influence is limited to 3.7 m.

We also examined the influence of the slope of the terrain by dividing the data in different slope intervals (from flat to steep). We found that the errors in elevation were higher for steeper slopes. The reason for this, which is logical, is that the evaluation points are located at a specified maximum distance from the cell center, resulting in a greater deviation in steeper terrain. These slope-related differences in accuracy within DEMs are often not noted, but should not be neglected as they may be significant. The accuracy of a DEM should perhaps be associated with the slope of the terrain,

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especially in high accuracy modeling on a detailed scale. Further studies are needed on this to develop more accurate DEMs, or at least document the weaknesses in DEMs when steep slopes are involved.

Based on the results in Figs. 4 and 5, and Tables 4 and 5, there is a strong indication that the median of the differences in drainage area is positive, while the median of the differences in slope is negative. This indicates that high resolution DEMs will estimate lower values of the drainage area than low resolution DEMs. Moreover, the slopes in high resolution DEMs seems to be overestimated compared to low resolution DEMs. This effect will be even more pronounced when calculating wetness indices, as these are normally based on the ratio between the slope and drainage area (see e.g. (Sorensen et al., 2006). Thus, higher wetness indices will be predicted using low resolution DEMs, and relatively low values when using high resolution DEMs.

7 Conclusions

We have studied the effect of changing the resolution of a DEM constructed from high precision LIDAR scanning data in a peatland area in northern Sweden. We have investigated and discussed the influence of resolution, search radius, and the slope of the terrain in relation to the accuracy in the estimation of elevation and drainage area. We also raised the issue of handling large amounts of data. Our main conclusion is that a limited search radius should be used in the interpolation algorithm, while ensuring that the number of known data points within this radius is adequate. The results clearly show that increasing the interpolation search radius leads to a decrease in accuracy of the DEM. Studying the spatial autocorrelation is valuable in determining the appropriate search radius.

Since peatlands are normally present in flat areas surrounded by steeper terrain draining into the mire, we also analyzed the possible effect of different terrain slopes on the accuracy of elevation estimates. This led to the conclusion that the accuracy of elevations predicted by the DEM differed for different slope intervals; being higher for flatter slopes.

Another conclusion of this study is that the accuracy of the slopes and drainage areas estimated by the DEM is highly dependent on the resolution of the model. The variation in these two topographical parameters greatly influences the wetness index, which is calculated by dividing the slope by the drainage area. It is suggested that coarse resolution DEMs result in higher estimates of drainage area, but lower estimates of slope, leading to a relative overestimation of wetness indices.

In complex terrain, consisting of steep slopes and flat areas, more accurate DEMs, and better knowledge concerning limiting factors, is necessary to construct accurate hydrological models. This is especially important in northern peatlands.

Further studies using high precision field data are recommended in order to clarify the relationships between DEM resolution and estimates of topographical/hydrological parameters such as wetness. It is obvious that high resolution field measurements, such as LIDAR data, have great potential in the development of DEMs suitable for relatively accurate estimates of hydrological processes in the landscape. One possibility in the future is to use regional and/or global LIDAR datasets to construct DEMs with acceptable accuracy to model the wetness in peatland areas, which in turn will facilitate future studies in global change.

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Table 1. The number of selected points for each DEM resolution out of the total 76 940 341 points.

DEM Resolution (m)	Maximum distance (mm)	Number of selected points
0.5	10	154 071
1	10	38 736
5	10	1579
10	10	417
30	10(30)*	57(230)*
90	10(50)*	6(68)*

* The distance was increased at resolutions of 30 and 90 to obtain a minimum of 60 points.

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Table 2. NMAD for the DEM with different combinations of resolution (cell size) and search radius (SR).

Cell size (m)	NMAD (mm)			
	1 m SR	2 m SR	5 m SR	10 m SR
90	29.7	44.5	59.0	82.0
30	29.6	44.4	59.3	88.9
10	29.7	44.5	59.3	74.2
5	29.6	44.4	59.3	88.9
1	29.6	44.4	59.3	88.6
0.5	29.7	44.5	59.3	74.2

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Table 3. Two quantiles for the different combinations of resolution (cell size) and search radius (SR).

Cell size (m)	Quantile (%)	Maximum error (m)			
		1 m SR	2 m SR	5 m SR	10 m SR
90	68.3 %	0.04	0.04	0.06	0.08
	95.0 %	0.082	0.10	0.10	0.24
30	68.3 %	0.03	0.04	0.066	0.10
	95.0%	0.09	0.12	0.17	0.23
10	68.3 %	0.03	0.04	0.06	0.09
	95.0 %	0.10	0.107	0.16	0.25
5	68.3 %	0.04	0.04	0.06	0.09
	95.0 %	0.10	0.12	0.17	0.26
1	68.3 %	0.04	0.04	0.06	0.09
	95.0 %	0.10	0.12	0.17	0.26
0.5	68.3 %	0.04	0.04	0.06	0.09
	95.0 %	0.10	0.12	0.18	0.26

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Table 4. Measures of accuracy showing that lower slope values are obtained with lower resolution of the DEM.

		Difference in slope (degrees)		
Accuracy measure	Error type	30 m–10 m	90 m–30 m	90 m–10 m
50 % quantile (median)	Δ slope	−0.372	−0.613	−0.879
NMAD	Δ slope	2.10	1.92	3.20
68.3 % quantile	|Δ slope|	2.36	2.19	3.69
95 % quantile	|Δ slope|	6.48	6.01	9.95

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Table 5. Measures of accuracy showing that larger drainage areas are obtained with lower resolution of the DEM.

		Difference in drainage area (m)		
Accuracy measure	Error type	30 m–10 m	90 m–30 m	90 m–10 m
50 % quantile (median)	Δ area	3133	21 480	29 205
NMAD	Δ area	3293	21 312	29 367
68.3 % quantile	|Δ area|	7090	43 974	55 927
95 % quantile	|Δ area|	62 793	264 322	292 635

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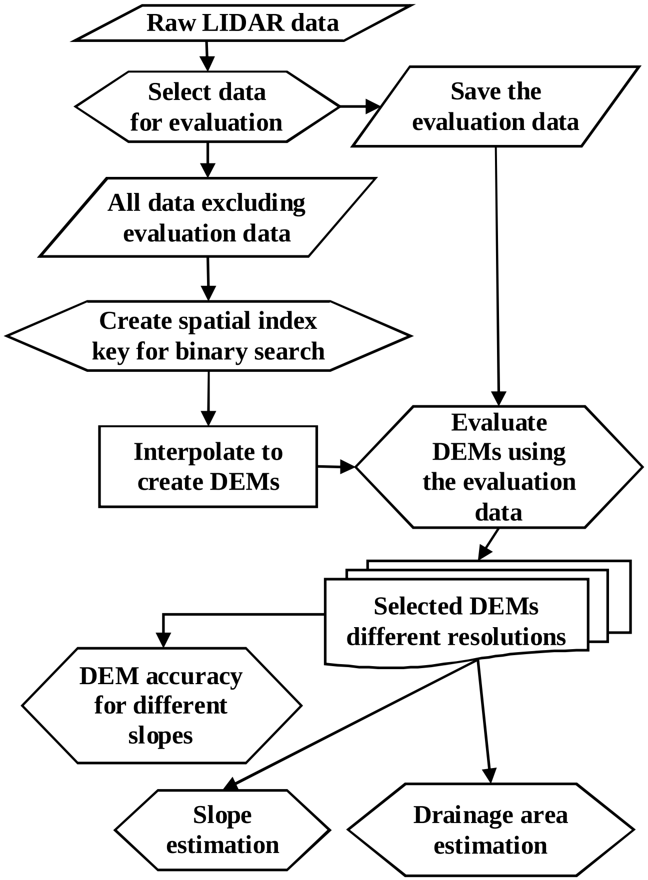

Fig. 1. General process used for the generation and evaluation of the DEM in relation to the interpolation parameters, model resolution, and the estimates of terrain slope and drainage area.

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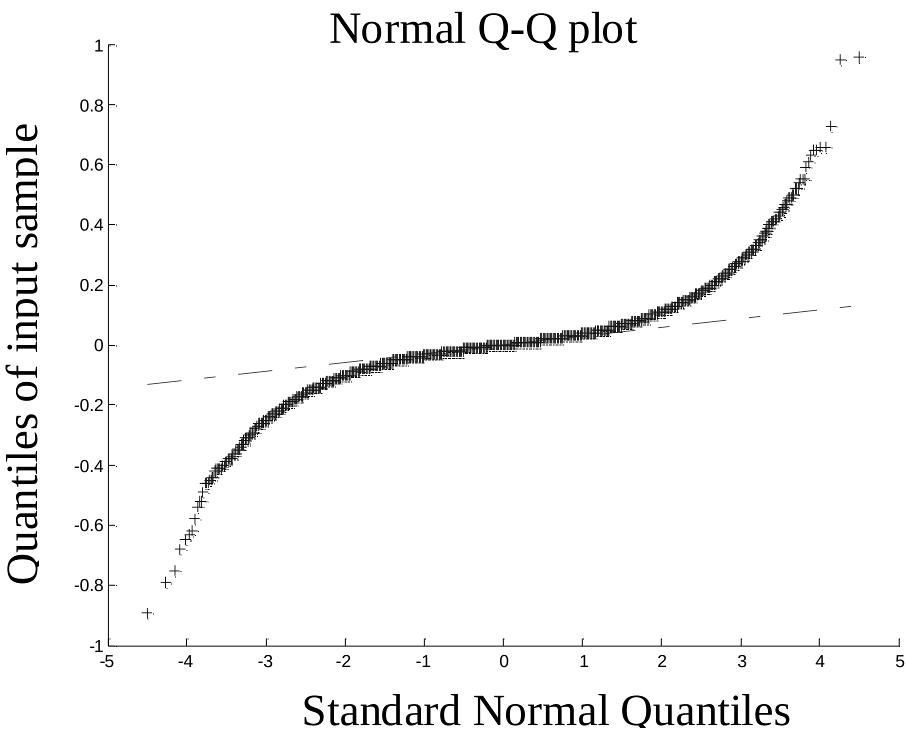

Fig. 2. Normal quantile- quantile plot for the error distribution together with the theoretical normal distribution for the DEM with 0.5 m resolution. The plot shows considerable deviation from a straight line.

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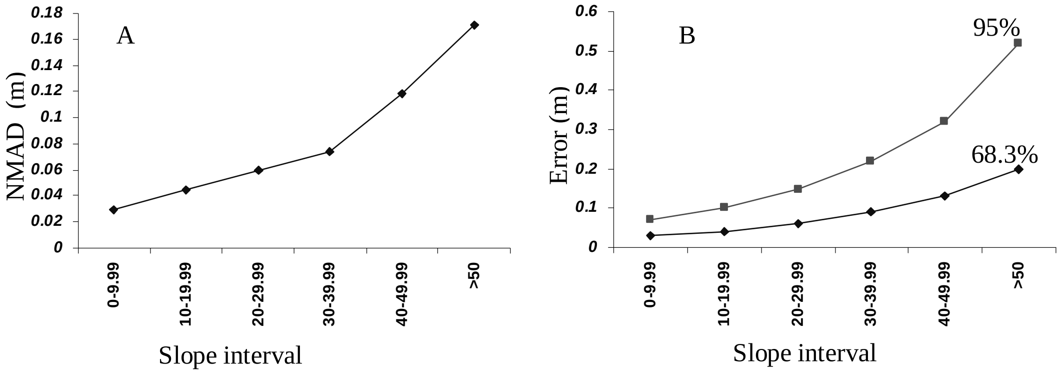

Fig. 3. The relationship between the slope of the terrain and the errors in the estimated elevation. **(A)** illustrates the NMAD for all data as a function of slope interval, while **(B)** shows the results for the 68.3 % and 95 % quantiles of the errors. Both figures are based on a resolution of 0.5 m.

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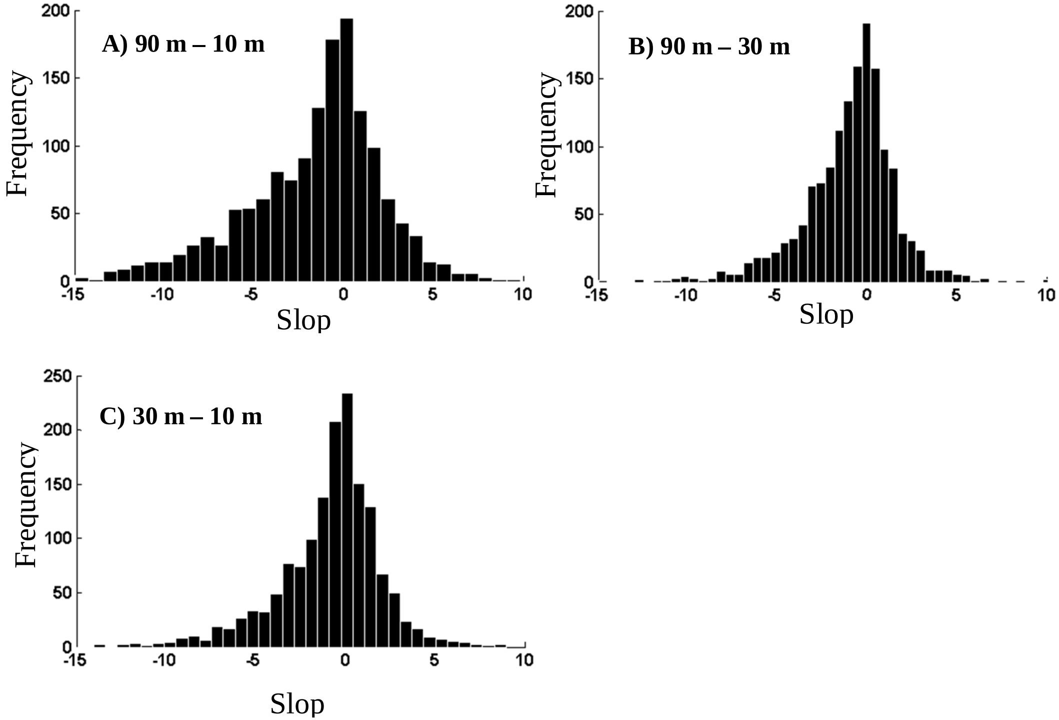

Fig. 4. The frequencies of the differences in the estimated slope using cell sizes of 10 m, 30 m and 90 m: **(A)** 90 m–10 m, **(B)** 90 m–30 m, and **(C)** 30 m–10 m.

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The use of LIDAR as a data source for digital elevation models

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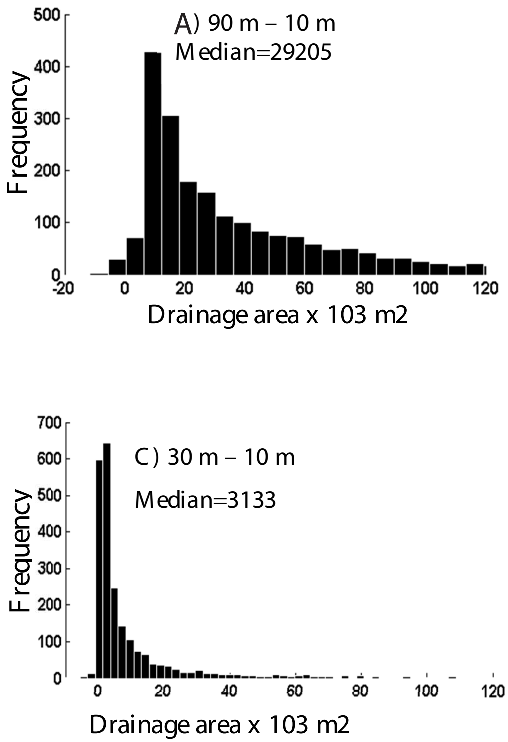

Fig. 5. The frequencies of the differences between the drainage areas estimated by the DEM at three resolutions: 10 m, 30 m and 90 m: **(A)** 90 m–10 m, **(B)** 90 m–30 m, and **(C)** 30 m–10 m.