DEM from topographic maps - as good as DEM from LiDAR?

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Abstract— **Digital elevation models play a significant role in geomorphological research. For geomorphologists reconstructing landform and drainage structure is frequently as important as elevation accuracy. Consequently, large-scale topographic maps (with contours, height points and watercourses) constitute excellent material for creating models in fine resolution. The purpose of the conducted analyses was to assess the quality of such topo-DEM and comparing it with a reference model derived from laser scanning (LiDAR-DEM). The analysis also involved derivative maps of geomorphometric parameters (local relief, slope, curvature, aspect) generated on the basis of topo-DEM and LiDAR-DEM. Moreover, comparative classification of landforms was carried out. It was indicated that topo-DEM is characterised by good elevation accuracy (RMSE <2 m) and reflects the topography of the analyzed area surprisingly well. For an area of several dozen km^2 topo-DEM with 10×10 m resolution proved more efficient than detailed (1×1 m) LiDAR-DEM.**

I. INTRODUCTION

Digital elevation models are commonly used in earth sciences and play a central role in environmental modelling across a range of spatial scales. There are many freely-available global DEMS (ASTER GDEM, AW3D30, DTED-2, EU-DEM, SRTM), but their quality is not always sufficient for conducted studies. If we talk about the local scale, DEM resolution of 25-30 m is usually too low. Obviously, low spatial resolution of the DEMs affects their low accuracy (horizontal and vertical). For this reason, higher resolution models must be used. As we know, nowadays the most accurate height data for creating high-resolution models are LiDAR data. Unfortunately, they are not always available for all interesting areas, especially if we are interested in comparative analyzes with historical data. Topographic maps come to our rescue, because they are an extremely valuable source of information about the heights and nature of the relief of a given area. Contour lines in combination with height points and water bodies and flows are great material for creating digital elevation models. The main goal of this study was to carry out investigations into the quality assessment of DEM derived from topographic maps (topo-DEM) for geomorphometric purposes. To achieve this goal it was decided to compare the accuracy of topo-DEM with reference to DEM derived from laser scanning (LiDAR-DEM). I tried to answer the questions: What is the vertical accuracy of topo-DEM versus LiDAR-DEM? and Can a topo-DEM produce similar results for geomorphometric analyses to LiDAR-DEM? To answer these questions comparison of elevation differences between a topo-DEM and a LiDAR-DEM were done, calculations of basic geomorphometric parameters and landform classification using Topographic Position Index were conducted.

II. DATA AND METHODS

Data that was used in this study were: topo-DEM and LiDAR-DEM (Fig. 1). topo-DEM was build on the base 4 sheets of the topographic maps in 1:10,000 scale [1]. Altogether, most of the contour lines (circa 750 km) and all 362 points with described altitude were digitized from the maps. I assumed that since the map scale is 10,000, the size of the smallest element on the map is 1x1 mm and in reality it is 10x10 m. So, I was decided to create a topo-DEM with the resolution of 10x10 m. topo-DEM was made in PUWG-1992 (EPSG: 2180) coordinate system, and the heights of points relate to the Normal Height System Kronsztadt 86 [2]. Digitalization, creating topo-DEM, all analyses and calculations, and DEMs visualizations were performed in the ArcGIS environment [3]. I have used the Topo-to-Raster tool from ArcGIS Toolbox to generate topo-DEM. The Topo-to-Raster tool creates hydrologically correct DEMs and is based on the ANUDEM algorithm developed by Hutchinson [4-5]. This method applies an interpolator specifically designed to create a surface that more closely represents a natural drainage surface and better preserves both ridgelines and stream networks from input contour data. Therefore, all the watercourses and water

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reservoirs with an area ≥ 500 m^2 were used as breaklines to support the interpolation process. LiDAR-DEM [6] is a DEM derived by Airbone Laser Scanning (ALS) method. This DEM has 1x1 m horizontal resolution, vertical accuracy of 0.2 m [7] and use the same as topo-DEM coordinate system (EPSG: 2180). The LiDAR-DEM was used as reference model.

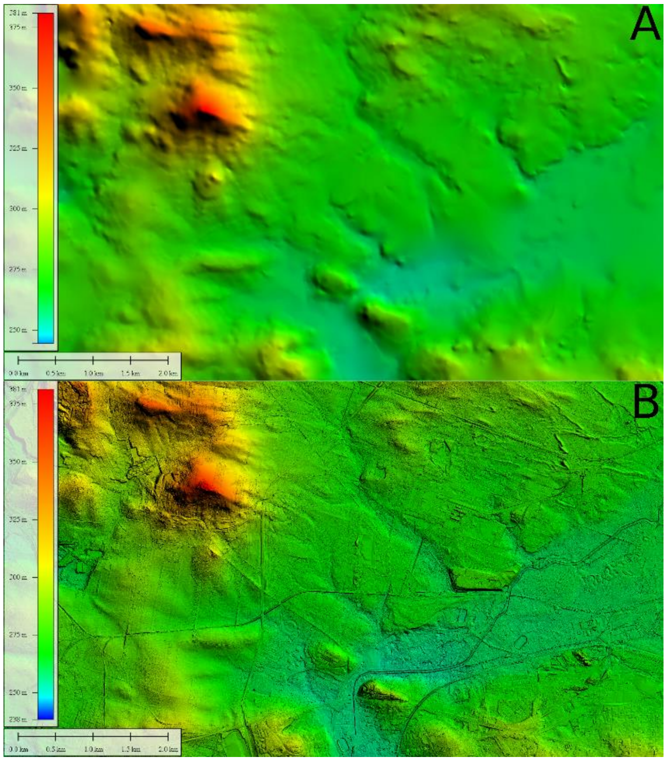

Figure 1. Fragment of the study area - hypsometry map on the base topo-DEM (A) and LiDAR-DEM.

The performed analyses can be divided into few stages:
First, the course of contours generated from the topo-DEM was compared with original contours from topographic maps. Then 100 checkpoints were randomly generated for which elevations read from the topographic map and from the topo-DEM were compared.
Second, reference data were derived by ground surveying with the application of high precision GPS RTK Leica Viva CS10. In total, 149 points for the entire area were measured. Distribution of checkpoints was not very regular because it was related to specific landform types (over 20 checkpoints in each type). Average accuracy of all the GPS RTK surveys was 1cm (horizontal) and 1.3 cm (vertical).
Third, detailed comparative analysis of topo-DEM with LiDAR-DEM was done. In the beginning elevation differences between topo-DEM and LiDAR-DEM were calculated. I used differential elevation map to show spatial distribution of elevational changes between both DEMs. I also used result conformity of elevations between DEMs, proposed by Szypuła [8]. This method consists in comparing both DEMs cell-by-cell and calculating the differences between them; values express how many percent of the first DEM grid cells are in accordance with the same grid cells of second DEM. The last basic geomorphometric parameters were calculated and compared.
Fourth, classification of landforms for both models using the Topographic Position Index [9] was made. TPI method is a classification system based on the difference between a cell elevation value and the average elevation of the neighborhood around that cell. Positive values mean the cell is higher than its surroundings (summit or near the top of a hill or a ridge), while negative values mean it is lower (at or near the bottom of a valley). TPI values near zero could mean either a flat area or a mid-slope area.

III. Results

3.1. topo-DEM versus source topographic maps

All the 10-m contours from the model were generated and compared with the original contours from the topographic maps. The vast majority of the contours generated from the topo-DEM exactly matched the original course of the contours from maps (so, the method has recreated a model with the same characteristics as the original). Next 100 checkpoints were randomly generated, for which elevations from the topographic maps were read and compared with the elevations obtained from the topo-DEM. The differences in the compared elevations ranged from -1.68 to +2.06 m. The values of the MAE and RMSE were < 0.2 m, and SD was 0.4 m, which is a very good outcome.

3.2. topo-DEM versus LiDAR-DEM - elevation differences

The histograms with elevation distribution of both DEMs are similar and show typical right-skewed (positive) distribution. This situation indicates the prevailing number of altitude values below average elevation values. Firstly, vertical accuracy of both DEMs was checked by comparing with GPS RTK measurements (the same locations read from the DEMs and measured in the field). LiDAR-DEM MAE value was only 0.13 m, and RMSE and SD 0.48 m (after checking it appeared that differences exceeding 0.75 m occur only in 4 points). The mean elevation of all checkpoints is also exactly the same as GPS RTK (Tab. 1). topo-DEM MAE value was 0.72 m and RMSE and SD less was 0.97 m. The biggest differences did not exceed 3 m (but only for 2 points). These are quite good results.

Table 1. Elevation differences between GPS RTK measurements and DEMs

DEM	Resolution [m]	Elevation differences [m]					Mean elevation [m a.s.l.]
		Min	Max	MAE	RMSE	SD	
LiDAR-DEM	1.0	-3.7	+3.4	0.13	0.48	0.48	288.2
topo-DEM	10.0	-3.6	+3.1	0.72	0.97	0.97	288.3

Then, elevation differences between topo-DEM and LiDAR-DEM were calculated. LiDAR-DEM was converted to 10x10 m resolution. The accuracies of topo-DEM can be described by maximum elevation differences: -20.48 m and +22.4 m. However, these extremely high values did not affect small MAE (1.16 m), RMSE (1.69 m) and SD (1.83 m) because errors bigger than ±10 m are only 0.34 % of all compared values. Fig. 2 shows spatial distribution of elevational changes between both models. The largest elevation differences occurred in places heavily transformed by man: a sewage treatment plant, a former coal mine or a rubbish dump. These are the areas with the smallest number of height information (the course of the contours was uncertain and often incomplete and there were no height points). Final values of result conformity was calculated for different elevation ranges: ± 0.1 m, 0.25 m, 0.5 m, 1.0 m and 2.0 m. It is interesting that more than 63 % of the study area has result conformity value for the height difference of ± 1m and for more than 86 % of the area it is ± 2 m. It generally shows how accurate topo-DEM is.

3.3. topo-DEM versus LiDAR-DEM - geomorphometric parameters

The following parameters were calculated: altitude, local relief, slopes, curvatures and aspect. Starting with the altitude one has to state that, despite the same resolution (10x10 m), LiDAR-DEM is much more detailed. This concerns elements related to human activity (embankments and road-rail incisions, excavations and dumps, artificial river channels, anthropogenic flats) in particular. The altitude range is very similar (LiDAR-DEM 239.1-381.0 and topo-DEM 244.4-380.8 m a.s.l. see Fig. 1). Maximum, mean and SD values of the altitude are practically the same.

Next, local relief - calculations were made in filter windows (3x3, 10x10 and 25x25 cells) to check how the values are distributed. Results showed that the biggest differences between the models occur for the 3x3 cells neighborhood. This situation confirms much greater detail of LiDAR-DEM compared to topo-DEM. The larger the filtering window (neighborhood) is, the more convergent and similar the results are.

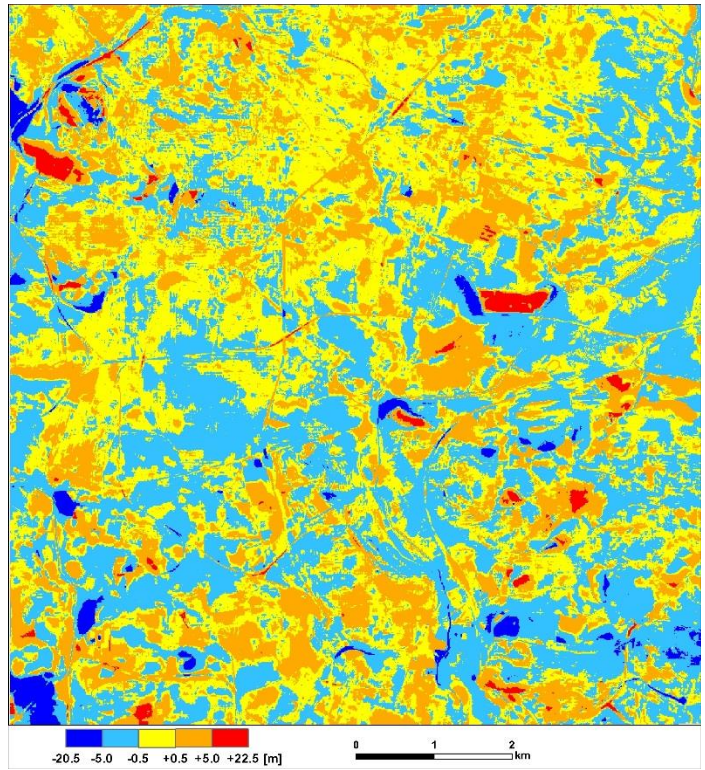

Figure 2. Map of elevational changes between LiDAR-DEM and topo-DEM

The spatial image of the calculated slopes is very similar to the local relief in the 3x3 cells neighborhood. Certainly, LiDAR-DEM showed a lot of small forms (lines of embankments and road incisions) that cannot be seen on topo-DEM. However, the main features of the relief are very clear. Higher maximum slope values occur in LiDAR-DEM but the mean and SD values are more similar.

The situation is different when we look at curvatures. Usually, expected values for an area with moderate relief can vary from -0.5 to +0.5, while for steep and mountainous relief the values can be much higher. In this case, a picture of spatial distribution is much more interesting than the values themselves. The curvature map on the basis of topo-DEM is clear and reflects and highlights characteristic elements of the topography well. Unfortunately, the map based on LiDAR-DEM is practically unreadable due to being too detailed (even though both maps are in the same resolution).

The last analyzed parameter was aspect. The distribution of the aspects, shows that a map derived from topo-DEM is much better for analyzing because the image is more generalized. LiDAR-DEM aspects introduce too much noise, so the picture is not clear.

The analysis of the polar plot and the percentage values for particular directions clearly show that the general quantitative-statistical picture is the same for both DEMs (differences in percentage from 0.3 to 1.7 %).

3.4. topo-DEM versus LiDAR-DEM - landform classification

I was decided to apply 10-class landform classification proposed by Weiss [9] (Fig. 3). In general, spatial distribution of the main landforms is similar. Classification on the basis of the topo-DEM is more balanced, slightly generalized compared to LiDAR-DEM. It seems that better visual effects are given by topo-DEM classification; the image is less overloaded. Although the reality is probably more efficiently reflected by LiDAR-DEM, the reception of the simplified (generalized) image is much better and easier to understand because we focus on dominant elements, avoiding unnecessary details. Moreover, quantitative analysis of landforms showed that results from both models were almost identical (the same statistical image).

IV. Conclusions

Elevation accuracy of the analyzed topo-DEM in 10x10 m resolution corresponds to the precision of the source topographic maps (1:10,000) with the MAE of 1-2 m and very close as compared with the LiDAR-DEM (MAE 1.16 m, RMSE 1.69 m and SD 1.83 m).

LiDAR-DEM converted to a 10x10 m (downsampling), is great DEM, but it turned out to be too detailed for studies of an area of this size (tens of km^2). This had a particularly adverse effect on maps with slopes, curvatures, aspects and landform classifications. Too much details caused information overload and blurred the spatial image, making maps unreadable. A topo-DEM coped well with the presentation of topography: it emphasized and reflected the most characteristic and dominant relief features. Maps of derived geomorphometric parameters and landform classification showed statistical and spatial distribution of the relief very well. These results confirmed the significance of geomorphological accuracy in geomorphometric analysis.

It should be remembered that topo-DEM is poor at dealing with low-relief areas due to the lack of detailed height information on maps. In these places, the high-resolution or even generalized (downsampled) LiDAR model is invaluable.

The above informations about topo-DEMs may be useful when: a) there is no high-resolution LiDAR DEM for the given area, but there are topographic maps that can be used to create a DEM; b) there is a need to create a DEM of a given area based on historic topographic maps and compare it with the contemporary DEM; c) topo-DEM can be used as reliable data to reduce the errors of freely-available global DEMs.

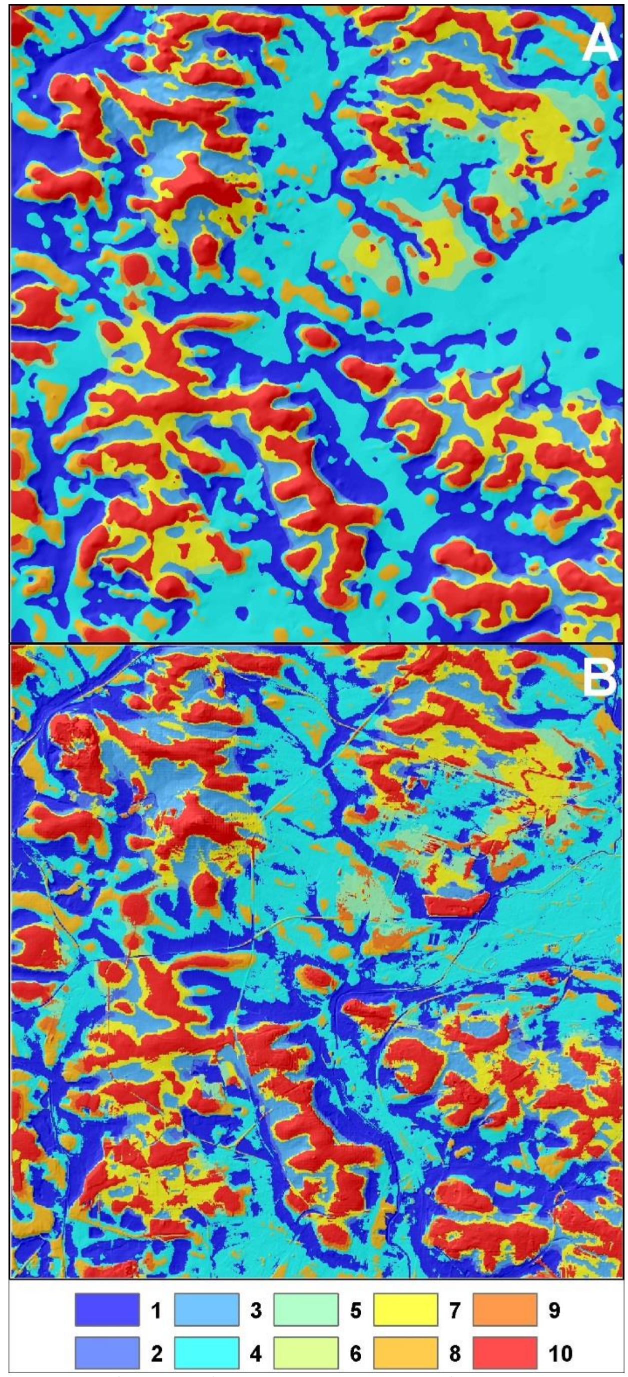

Figure 3. Landform classification using TPI method after Weis [9]on the base topo-DEM (A) and LiDAR-DEM (B): 1 - incised streams, 2 - shallow valleys, 3 – headwaters, 4 - wide valleys and depressions, 5 - small plains, 6 - open slopes, 7 - upper slopes, 8 - local ridges, hills in valleys, 9 - midslope ridges, small hills in plains, 10 - tops, high ridges

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