Effect of digital terrain model resolution on topographic parameters calculation and spatial distribution of errors

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ABSTRACT: Digital terrain models (DTM) have become a commonly used source of data describing the shape of the Earth. Resolution determines the level of details that can be represented in this model. Changing the resolution influences the accuracy of the DTM. The effect of a resolution is even more clearly seen in slope and aspect calculation. Despite the resolution, there are different methods of acquiring DTM that contribute errors. Each method requires its own algorithms for data management and its own interpolation techniques. Some of the most popular methods are: laser scanning (LiDAR), photogrammetric measurements on pairs of aerial photos or satellite images, digitizing contour lines from topographic maps and InSAR measurements (e.g. SRTM model). Both resolution and acquiring method as well as many other factors constitute the overall error of a DTM. The knowledge of its size is the key information for the DTM user and is required for proper use of a model. Each research requires a specific level of accuracy which depends highly on the nature and scale of the research. For most terrain models errors are estimated with RMSE statistic. It is calculated by comparing cells in DTM with control points representing “true values”. The main objective of this research is to investigate how horizontal resolution influences vertical accuracy of a DTM and how it influences calculation of slope and aspect. The general approach is to generate DTM, slope and aspect covering the same area with 1, 5, 10, 25, 50 and 100 m resolution for all four methods of acquiring elevation data. Moreover, the results of analysis of four different models have been compared with LiDAR model. All cell values from this model were used as a reference in statistics calculation. Basic statistics as well as spatial distribution of errors were examined according to different resolutions.

1 INTRODUCTION

Digital terrain models (DTM) have become a commonly used source of data describing the shape of the Earth. Most of them use a raster data model that stores an elevation value in a cell matrix. Using raster models means faster computation but at the expense of fitting regular grid to naturally irregular reality. The resolution determines the level of details that can be represented in this model. Changing the resolution influences the accuracy of the DTM. This influence, however, depends on the type of a particular terrain relief (e.g. mountain and hilly regions versus lowlands).

The effect of a resolution is even more clearly seen in a slope and aspect calculation. These two topographic parameters have a great impact on many natural processes (e.g. intensity of erosion, amount of accumulated solar radiation). They are very often used
for modelling different processes. Despite the resolution, there are different methods of acquiring DTM that contribute errors. Each method requires its own algorithms for data management and its own interpolation techniques. Some of the most popular methods are: laser scanning (LiDAR), photogrammetric measurements on pairs of aerial photos or satellite images, digitizing contour lines from topographic maps and InSAR measurements (e.g. SRTM model).

Both resolution and acquiring method as well as many other factors constitute the overall error of a DTM. The knowledge of its size is the key information for the DTM user and is required for the proper use of a model. Each research requires a specific level of accuracy which depends highly on the nature and scale of the research. For most terrain models errors are estimated with RMSE statistics. It is calculated by comparing cells in DTM with control points representing “true values”. This assessment does not provide any information of how well each cell represents the real elevation and what the spatial distribution of errors is.

The main objective of this research is to investigate how horizontal resolution influences vertical accuracy of a DTM and how it influences calculation of slope and aspect. The general approach is to generate DTM, slope and aspect covering the same area with 1, 5, 10, 25, 50 and 100 m resolution for all four methods of acquiring elevation data. Moreover, the results of analysis of four different models have been compared with a LiDAR model. Its resolution was 1 m and vertical accuracy was approximately 0.2 m. All cell values from this model were used as a reference in statistics calculation. This approach enabled to compare 100% of data in each DTM with reference data. Basic statistics as well as spatial distribution of errors were examined according to different resolutions.

The study area is located near Torun in central Poland. It is a 2 x 2 km test polygon, covering part of the Vistula river and its valley. The largest area is occupied by a flat floodplain, mostly used for extensive farming. On the terrace above there is an extensive house construction. On the north there is a steep slope of a Vistula terrace system, with a slope reaching up to 45 deg. This part of the Vistula river has no dike system, which causes a high natural hazard of floods.

2 METHODOLOGY

The resolution which affects the accuracy of a digital terrain model is a key problem for all DTM users. Many researches have been focused on assessing vertical as well as horizontal accuracy of DTMs. Some of them focus on particular systems and models (Miliaresis & Paraschou 2005). Other authors create and describe different methods of accuracy assessment (Acharya et al. 2000). A lot of attention has also been paid to investigate the effects of resolution and other DTM attributes on accuracy of digital terrain models (Zhou & Liu 2003; Thompson et al. 2001).

The basic idea of this research was to assess the accuracy of different resolution digital terrain models by investigating their statistic characteristics and comparing their cell values with reference LiDAR models. Four digital terrain models covering the same study area with different resolutions and from different elevation data sources have been generated. Elevation data from LiDAR, photogrammetry, contour lines and InSAR (SRTM) have been acquired.
The accuracy assessment process performed in this research consisted of several steps:

- input data preparation,
- slope and aspect models calculation,
- comparison of digital terrain models, slope models and aspect models with reference LiDAR models,
- statistic description of input and output datasets,
- presentation of results in form of tables, graphs and maps,
- conclusions.

For this research, ArcView software with Spatial Analyst extension has been used.

2.1 Input data preparation

Firstly, all the input elevation datasets had to be preprocessed and unified according to file format and spatial reference (coordinate) system. In this research all the datasets were transformed into PUWG 1992 which is a projected coordinate system commonly used in Poland. All the data files were stored in ESRI-supported formats: shapefiles for vector datasets and grid for raster datasets.

Then, the data were used to generate digital terrain models. All DTMs were prepared in six different resolutions for all four methods of acquiring elevation data. In this way 24 digital terrain models were created. The next step was to calculate slope and aspect models for all of these DTMs. In total, 72 input grid datasets were used for the analysis: 3 types of datasets (DTM, Slope, Aspect) in 6 different resolutions (1, 5, 10, 25, 50 and 100 m) for all four methods of acquiring elevation data (LiDAR, photogrammetry, contour lines and SRTM). All grid datasets were generated with “Snap Raster” setting, which ensures the cell alignment. The lower left corner and upper right corner of all datasets were snapped to the nearest cell of the reference model.

Since each method of acquiring elevation data uses different procedures and different file and data formats, all the input data transformations according to each method should be described in more details. A short description of all the transformations and algorithms used for each method has been made below. The main aim of this summary is to show what is the way of processing the elevation data from the raw data to DTM. We also need to bare in mind that all of these transformations introduce errors and distort original data. Even so, they need to be done in order to use a DTM in a proper format and in a required coordinate system. The end user of a DTM, however, has to be aware of these transformations and of potential errors that may affect his analysis.

2.1.1 LiDAR model

The source text file containing filtered LiDAR measurements (x, y, z) has been imported to shapefile format (*.shp). All the points were directly used to interpolate grid DTM with 1 m resolution (since that was the approximate resolution in which LiDAR measurements were done). Natural Neighbor technique which produces little distortions of original values and ensures fast computation of large datasets was used for the interpolation. Output grid was considered a reference model for accuracy assessment of all other digital terrain models. For purposes of this research a LiDAR model with 1 m
resolution was assumed as 100% accurate, representing “real” terrain elevation. It was also used for generating LiDAR DTMs with 5, 10, 25, 50 and 100 m resolution. The AGGREGATE algorithm was used for a generalization process. Each pixel in 5 m DTM was calculated as a mean value of all 25 pixels in 1 m resolution model.

2.1.2 Photogrammetric model
Photogrammetric data often come in DXF/DGN format, as they are manually or automatically digitized on aerial stereophotographs. For this research, elevation datasets consisting of hard breaklines, soft breaklines, elevation points, water body boundaries and contour lines were used. All the layers were originally stored in DXF format. They were converted to shapefiles and a TIN model was built. Finally, grid digital terrain models were generated with the use of Tin To Raster function.

2.1.3 Contour line model
Contour lines were acquired from digital version of Polish topographic map in the scale 1:10 000. They were originally stored in DXF format. All the contour lines as well as some other elevation features available on the map (e.g. water bodies, rivers, elevation spots) were converted to shapefiles. They were used for TIN model calculation and finally converted to grid models.

2.1.4 SRTM model
For this research the InSAR SRTM DTED-1 (Level 1) model was used. Its resolution was 3 arc second (approx. 90 m). It was downloaded from USGS server (http://seamless.usgs.gov). Although SRTM model is already available in a grid format it had to be transformed in order to fit the proper coordinate system and match all the pixels in other models. The transformation required conversion from a grid to points and a Kriging interpolation back to the grid format. This fact highly distorted the original data, but it was necessary to perform a comparison with a reference model.

2.2 Calculation of slope and aspect models
All digital terrain models were used for calculation of slope and aspect models. As a rule a 1-m resolution model was used for generating a 1-m resolution slope model as well as a 1-m resolution aspect model. The same rule applied to all other resolutions. SLOPE and ASPECT algorithms available in ArcView Spatial Analyst extension were applied for these calculations. Both output data types were calculated in degrees.

2.3 Comparison with reference LiDAR models
For a comparison of all input datasets (digital terrain models, slope models and aspect models) with a reference model a Model Builder tool was used. During the comparison basic mathematic operations were performed on grid (cell) values. An example of such a comparison for contour model is shown in Figure 1.

As shown in Figure 1 each model was first subtracted from the reference model. The output error values indicated the difference between each pixel value in comparison with reference data. In the case of digital terrain models negative values indicated that the
Elevation was lowered while positive values indicated higher elevation than “real” value. For slope and aspect models the difference was measured in degrees and it referred to a slope angle and an aspect azimuth respectively.

Secondly, all the values of the output were squared, square rooted, and finally aggregated to input model resolution in order to show the mean error in each input cell. A statistic description of all input and output datasets were summarized in form of tables and graphs. They were also visualized (mapped) to show the spatial distribution of errors. In this way it was possible to correlate error values with different forms of terrain relief.

3 RESULTS AND DISCUSSION

3.1 Digital terrain models

Changing the resolution has little effect on minimum, maximum and mean elevation values for all digital terrain models (see Figure 2). Generalization of models slightly reduces extreme values (both minimum and maximum) and creates smoother terrain.

The result of generalization is, however, clearly seen while calculating differences between each model and reference models (see Figure 3). The maximum positive and negative differences are growing with increasing size of a pixel. For a 5-m LiDAR model the extreme differences are \( \pm 2.5 \) m, for \( r = 25 \) m: \( \pm 6.9 \) m, \( r = 100 \) m: \( \pm 16 \) m.

As shown in Figure 3 for LiDAR, photogrammetric and contour models extreme errors have normal distribution, which means that maximum positive and negative error values are similar for specific resolution. Only for SRTM model extreme errors do not change with resolution and they are almost constant.

3.2 Slope models

The effect of resolution is even more clearly seen in slope calculation (Figure 4 and 5). This is due to the fact that slope is calculated based on 8 neighbor cells, that makes slope more sensitive for resolution changes. In all models minimum slope is 0 deg. and it does
not change with increasing size of a pixel. We can observe the biggest changes in maximum slope values. In models with 1-m resolution, slope values reach up to 60 deg. in photogrammetric model and only 24 deg. in SRTM model. These values are significantly reduced with a decreasing resolution.

Figure 2. Maximum, minimum and mean elevation values in DTMs.

Figure 3. Extreme positive and negative errors in DTMs.
For all models decreasing a resolution significantly reduces a maximum slope value. For a reference model (with resolution $1 \text{ m}$) a maximum slope of 53,82 deg is registered within the test polygon. For all other LiDAR models this value decreases with the resolution ($r$) and is equal to 30,66 deg for $r = 5 \text{ m}$, 25,26 deg for $r = 10 \text{ m}$, 19,45

Figure 4. Maximum slope in slope models.

Figure 5. Extreme positive and negative slope errors in slope models.

Effect of digital terrain model resolution on topographic parameters calculation 621
deg for \( r = 25 \) m, 13.31 deg for \( r = 50 \) m and only 6.98 deg for \( r = 100 \) m. Similar situation referred do photogrammetric and contour models. This trend could be also seen for SRTM models, although the maximum slope for \( r = 1 \) m is only 23.90 deg, while for \( r = 100 \) m it is 8.29 deg and it is comparable with other models, generated from elevation data acquired with different methods.

It is not only the maximum slope value that tends to be lowered with a decreasing resolution. Changing the resolution affects all slope values, especially in hilly terrains. In the case of a test polygon a slope value on the slope of a Vistula terrace system in the northern part has been lowered the most. Although the width of the slope is more than 100 m and its average slope is 20–30 degrees even in models with \( r = 50 \) m the maximum slope is not more than 14 degrees.

Although the minimum and maximum elevation values in DTM have not been changed significantly, the effect of resolution change is significant in the case of slope calculation. It has to be considered in many practical usages of DTMs. In such researches as analysis of erosion or terrain diversity it is crucial to choose a proper resolution. In other case, too coarse resolution may affect and change the results of such analyses. In such cases it seems that \( 1 – 10 \) m resolution DTM should be used for slope calculation. Coarser resolution of a DTM will introduce significant bias of slope model and will influence the results.

Generally, the biggest errors in slope calculations refer to steep slope areas, which are usually most important in researches (e.g. due to natural hazard risk). Therefore, more accurate and high-resolution DTM should be used in this kind of research.

3.3 Aspect models

The accuracy assessment of aspect models has mainly been based on percentage of pixels classified to different aspect directions (Figure 6, 7, 8, 9). This classification reveals that South-West and South aspect dominate in the study area. It is due to the fact that a steep slope of the Vistula valley faces these directions. In all aspect models values of these two directions were the most frequent while values of East directions (NE, E, SE) were least frequent.

The results show that an increasing size of a pixel (lower resolution) caused even higher disproportions between South-West and East direction classes. In LiDAR model the number of pixels classified to SW was rising along with a decrease of resolution from 16.98% (for \( r = 1 \) m) up to 35.75% (for \( r = 100 \) m), while the share of SE pixels was decreasing from 10.69% (for \( r = 1 \) m) to 3.75% (for \( r = 100 \) m). A similar trend can be seen for all four methods of acquiring elevation data, although the percentage values differ quite significantly. This difference was caused mainly because of different areas of pixels classified as flat surfaces in each model.

Significant influence on the total number of flat pixels can be observed both for different elevation data acquiring method and different DTM resolution. The largest flat area was recorded for contour aspect model (\( r = 1 \) m) where its share was almost 40%. For the same resolution SRTM model none of the pixels were classified as flat areas.

It is clear that a resolution affects the number of flat pixels significantly. The rule is that the number of flat pixels decreases with increasing size of a pixel. For a 1-m contour aspect model the share of cells classified as flat was 38.82% while for \( r = 100 \) m it was only 1.5%.
Figure 6. Aspect classes (in %) in LiDAR model.

Figure 7. Aspect classes (in %) in photogrammetric model.
Figure 8. Aspect classes (in %) in Contour model.

Figure 9. Aspect classes (in %) in SRTM model.
The results also indicate that the biggest errors in derived aspect values refer to rather flat areas. The cell is classified as flat only if it is surrounded by cells with exactly the same elevation value. It is the input data transformation process (e.g. interpolation technique, data precision) that influences the final aspect calculation. As a result, steep slope areas are less probable to contain errors in aspect calculation rather than flat areas. This is opposite to derived slope values.

4 CONCLUSIONS

This research has shown how horizontal resolution influences the vertical accuracy of a DTM and how it influences slope and aspect calculation. Moreover, some of the most popular methods of acquiring elevation data are compared with respect to the resolution of a model.

Conclusions can be summarized as follows:

* the resolution has a significant influence on a DTM accuracy, as well as on slope and aspect calculation,
* decreasing the resolution (increasing a cell size of a DTM) causes generalization of a model, reduces extreme elevation values and increases the overall error of a DTM,
* the influence of elevation data acquiring method has a significant influence on a DTM accuracy only for high-resolution models (from 1 to 25 m). Models with coarser resolution (above 50 m) do not differ significantly.
* independently from the elevation data acquiring method high-resolution digital terrain models (1 to 10 m, depending on the aim of the research) should be used in slope calculations.
* for large-scale analysis, requiring low-resolution models (e.g. for reduction of data capacity or for visualization purposes) SRTM model can be used.
* in order to increase the accuracy of contour models additional information such as elevation points, hard breaklines, shorelines should be used for DTM generation.
* minimum transformations should be done while processing the data in order to reduce biases and distortions that occur on every step of DTM generation.

Further research should be done to compare the effect of resolution in different terrain types (e.g. mountains vs. lowlands). Moreover, the influence of different interpolation techniques and different data processing algorithms should be examined in accordance to DTM accuracy. Finally, other topographic parameters should be examined with respect to DTM resolution and elevation data acquiring methods.

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