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METHODS OF IDENTIFICATION AND DELIMITATION OF CONCAVE TERRAIN FEATURES BASED ON ISOK-NMT DATA

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Abstract

Airborne Laser Scanning (ALS) products are now often used to study the terrain due to their numerous advantages such as relatively low cost and ease of data collection. The ISOK project (pl: Informatyczny System Osłony Kraju – national hazard protection information system) developed elevation data for about 65% of the Polish territory. Parallel to the airborne laser scanning point cloud collection, additional products, such as orthophotomaps, digital terrain models (DTM), and digital surface models (DSM) were created. This resource is not only a reference material for the project, but also a valuable source of the analysis used in various fields of economy and science. Important features of the ISOK-data are the availability and their standardized format based on uniform technical conditions. The article presents the results of an experiment in which an attempt was made to use the digital elevation model with a resolution of 1 m based on airborne laser scanning data to determine concave terrain features using GIS tools. The ISOK-DTM has a height accuracy of 0.15 m for the outdoor areas, which makes it a better representation of small terrain forms than previous products. The research area is located at an undeveloped open ground with comparatively little variation of its shape for a long period. Several methods were tested to classify the terrain shape based of topographic attributes. Those methods led to similar locations of the concave features and further on coincide with results of the pre-analysis. Also, attention was drawn to the selection of the analysis parameters and their influence on the result. The results show the usefulness of ISOK's DTM for locating field concave terrain shapes.

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Introduction

The shape of the terrain has a significant impact on the phenomena on its surface. The characteristics of the topographic surface and the presence of certain land forms determine the development and the usage of the area. Identification of particular landforms based on measured elevation data facilitates land use planning and the better understanding of land cover and phenomena occurring on it. Concave terrain forms, i.e. sinks, are one of the very important ones as they may be suitable as water catchments. Regardless of the terrain's inclination forms such as local depressions, sinks, wells or other synclinal forms interferes with the surface water runoff (Fig. 1). This may cause permanent or periodic wetness accumulation.

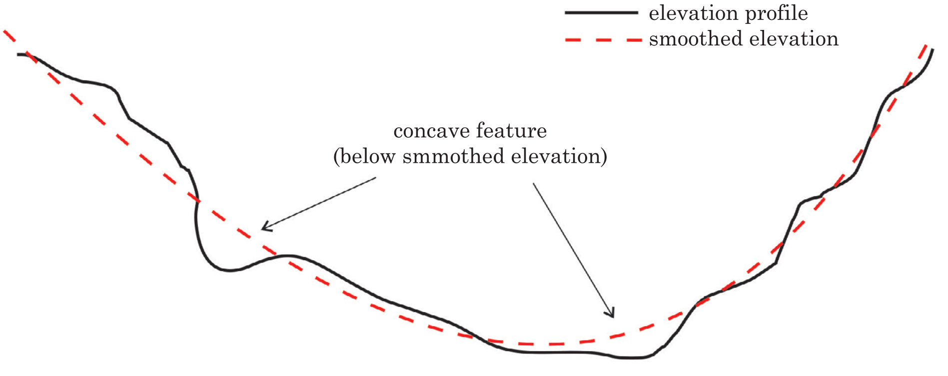

Fig. 1. Sample of concave features

Under some conditions the presence of concave forms can be a reason of accumulating material transported with the runoff of surface water. After a long period the accumulated material can change the surface characteristic for example by filling up the concave sites. This happens in areas covered with loose materials and high runoff intensity. Another case occurring in rural areas is filling sinks with organic matter derived from the decomposition of plants, and sometimes chemicals such as residuals of fertilizers and herbicides. Concave areas promote the accumulation of the water and due to the increased humidity may give an unfavourable environment for the growth of crops. As a result of excessive moisture at these sites anaerobic conditions may temporarily or permanently support decomposition processes. They are usually formed at local, mild synclinal forms, e.g. concave parts of the slopes. A dense measurement of the topographic surface is required to identify such features. Airborne Laser Scanning technology due to its ability to pass through openings in the canopy and to detect the underlying surface of the Earth can provide fairly dense data in forested or inaccessible areas. Measured points of the ground in areas usually obscured by vegetation support analytical methods of wetland delineation (UDWIG 2015) or channel networks mapping (KLADZYK 2015). This kind of measurement has been made recently by airborne laser scanning (ALS) in Poland in the frame of the ISOK (pl: Informatyczny System Osłony Kraju, national hazard protection information system) project. Airborne laser scanning (ALS) is now a widely used method of spatial data collection. With a combination of techniques for determining the position and the inclination of the measuring instrument (GPS, INS) and a system for measuring the flight time of a laser beam from its point of generation to the point of reflection and back it is possible to generate a point cloud representing the shape of the scanned surface. The scan frequency, and thus the density of the point cloud obtained is selected according to the needs and costs. The higher the frequency the more points are saved and thus the scanned object is mapped in a more detailed way. However, this increases the cost of data acquisition and generates larger files, and requires more resources during post processing. Laser scanning technology has been used already in Poland for a few years. Several domestic companies offer services in laser scanning. So far, studies were made locally and globally. Local studies include commercial tasks, e.g. the modernization of the rail network, or research and development for scientific institutions. The global studies include the ISOK-project as a part of an efficient system of the country protection against extreme hazards. The scanning was performed in years 2011–2013 during spring and autumn. In order to adapt to different terrain types scanning was done with two different setups. The first setup was defined for urban areas with a high point density of 12 points/m^2 while the second setup with a density of 4–6 points/m^2 was defined for the remaining area (KURCZYŃSKI, BAKUŁA 2012). After quality control the ISOK datasets have been made available as a part of National Geodetic and Cartographic Resource. Data such as point clouds in LAS format, orthophotos, digital terrain models and digital surface models are available for many applications. Now, high accuracy photogrammetric data are covering about 65% of the Polish territory. It is a good reference for comparative studies in different regions of the country because of its standardized data capture and processing, as well as the high up-to-dateness. The whole data was collected in relatively short time period so topographic situation shows same land use level. A digital terrain model (DTM) is one of the ISOK products. It was interpolated as a square grid based on the LIDaR point cloud. The best available resolution of the resulting gridded DTM is 1.0 m $\times$ 1.0 m. It is prepared on the basis of the point clouds obtained by the specification of the first and the second setup. According to the standard rules the DTM accuracy defined as the mean height error is assumed as 0.15 m for well defined uncovered area, and 0.25 m – 0.30 m for forested areas. The error of steep, hilly and forested slopes may be larger. The DTM has been saved as a text file containing the x, y, z coordinates. It is not associated with any specific software. Thus, it is possible to load the data into any GIS/CAD environment.

Methods

The topic of identifying and delineating concave forms was repeatedly addressed in scientific research. It is a very important issue regarding crisis management, natural disasters like floods, and other. The automatic methods of the localization of such sites by using a DTM could be applicable in many areas. The automatic methods are very helpful for some types of simulations based on the terrain shape, e.g. to determine the extent of the floods, to estimate probable losses and to plan preventive actions. A similar situation can happen in areas not covered by permanent flood monitoring, i.e. where no hazard maps are developed. There, problems of water management may happen due to the shape of the topographic surface. In such situations an overview of the DTM in conjunction with other available hydrographic survey materials helps to understand these phenomena and develop possible solutions, for example insulation or drainage (OBERSKI, SZCZEPANIAK 2013). Using GIS tools with DTM data on land use planning helps to find those areas which periodically collect water due to depressions. Such places inconvenient for several usages should be excluded from becoming construction sites (BIELSKA, OBERSKI 2014). Research carried out by the author showed the usefulness of GIS analysis using DTM data in locating natural bodies of water for undeveloped areas as methods to support landscaping (OBERSKI, ZARNOWSKI 2013).

An experiment was conducted in an area of an undeveloped agricultural region with comparatively little variation in the terrain shape over a long time. Due to the land use type (agricultural crops) it is possible to observe phenomena on the surface characteristic for different seasons, under different stages of plant growth, and „bare" earth. The location of the test area is shown on Figure 2.

It is located in the municipality of Stawiguda, district Olsztyn in Warmia-Mazury. The area has an undulated terrain. Glacier erosion as well as runoff, snowmelt and river water activities has formed the relief. The area is mostly plateau originating from the accumulation of moraines reaching up to a height of 120 m – 140 m above sea level. This upland has an early glacial terrain relief. The terrain's shape is undulating with convex forms (eskers, moraine hills) and concave forms as parts of river valleys and glacial. A characteristic feature

Fig. 2. Location of test area

of this area is the presence of numerous septic sinks and wells. Moraines have the form of individual, irregularly spaced hills (GLIŃSKA-LEWCZUK 2012). The detection of significant concave forms in the rural area can be done in-situ quite easily. However, this depends on periodically occurring factors such as time of year, hydrological conditions and vegetation cover. In the case of an impossible site's inspection archived photogrammetric materials can be used. The best and most independent data source is a DTM. The quality of the points of interest based on a DTM depends on its density and the height accuracy. If the DMT's grid is not dense, it is still possible to identify concave forms in regions of clearly distinguishable landforms such as saddles, sinks, and depression. However, due to a lack of visual comparison with surrounding points the boundaries of the concave areas are more difficult to determine in that way.

Of course, this method is not perfect and not suited for minor concave forms, especially those which define the characteristics of the terrain. Small discrete concave forms are not always found at the lowest parts of the study area. Due to irregularities of the terrain undulations they are often included in other landforms which do not exactly correspond to depressions. They may be located in a slightly concave parts of slopes or on hill tops. The examination of neighbouring cross sections is one of the primary method to determine recessed areas. This leads to the identification of barriers blocking superficial water runoff according to its average slope (OBERSKI, ZARNOWSKI 2012). Automatic or semi-automatic comparison of cross-sectional shapes allows the identification of concave forms. However, due to the two-dimensional nature of the analysis the delineation of those areas is only approximate.

The identification and the delineation of concave field forms is also possible with GIS tools. Software environments such as SAGA-GIS or ArcMap offer many opportunities to solve that task. Especially the Spatial Analyst Tools are very useful. By using several terrain analyst tools it is possible to find regions where surrounding points are higher and the slope is always directed to the inside. This phenomenon can occur anywhere on topographical surface, regardless of the height above sea level and its occurrence may not be related to the general direction of terrain slope. By applying a combination of ArcMap's Spatial Analyst functions Focal Flow, Flow Direction, Sink, Watershed, and Zonal Fill it is possible to recondition the DTM in order to create a „hydrologically correct" elevation model. A hydrologically correct elevation model is one in which every pixel in the surface slopes continually down gradient and out the edges of the elevation model boundaries. In this way concave terrain forms are filled in and equalized. Once they are filled, it is easy to locate differences between the original DTM and the corrected one. There are also several ways to find concave terrain features based on a DTM grid. The Topographic Position Index (TPI) is useful for landform classification which includes concave features. TPI is the difference between the cell elevation value and the average elevation of the neighbourhood (KOZIOŁ 2009).

$$\mathrm{TPI}(D)_i = h_i - \frac{\Sigma h_j}{n} \tag{1}$$

where:
h_i – height level in analysed cell,
h_j – height of cells that surrounds analysed cell,
n – number of surrounding cells.

The neighbourhood defines the extent of the area around the centre cell by defining a number of elevation points. Commonly used neighbourhood shapes are circle, rectangle or ring (circle with a circular hole). Usually, the type of the neighbourhood is selected empirically. Some researchers have used other shapes to distinguish specific forms. However, for this project a circular neighbourhood was used. Positive values of the TPI indicate a cell higher than its surroundings. Negative values indicate lower cells. TPI values around zero could either mean a flat area or a regularly sloped area.

The landforms classification needs more input data to give satisfactory results. Especially when TPI values are near zero it is necessary to check the terrain slope. Combination of slope and TPI values helps to distinguish between flat and constantly sloped areas. The size of the neighbourhood which determines the number of cells for computing the average elevation is crucial for the TPI values. It depends on the size of the neighbourhood, i.e. the radius of the circular area, the size of the rectangle, or the ring's radii. Therefore, TPI values depend on the scale factor describing the neighbourhood's size. The TPI is very scale dependent. In practice it is necessary to use several scale factors to choose the most convenient for a specific area. It is important because the TPI based landform classification may find a flat plain, convex forms or concave forms in the same location (JENNESS 2006). An example is shown in Figure 3.

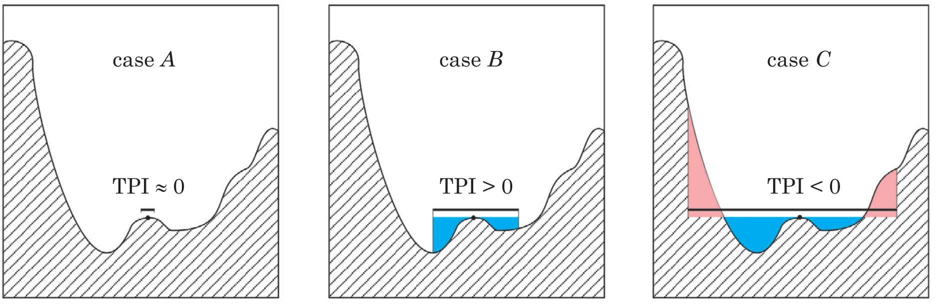

Fig. 3. TPI values for one location at three different scales (cases: *A* – small scale makes no difference between elevation of cell and neighbourhood, so TPI value is approximately 0; *B* – analyzed cell is distinctly higher then neighbourhood so TPI value is greater than 0; *C* – the neighbourhood includes the hills on either side of the valley, therefore, the analysed cell is lower than its neighbours and thus the TPI value is negative

Source: http://www.jennessent.com/downloads/TPI_Documentation_online.pdf, 2015.08.25.

The correct understanding of the scale as one of the main factors influencing the TPI values allows a precise analyses of the results. In general the TPI for the small scale enables the delineation of local hills and pits while the large scale helps to locate larger forms like valleys and mountains. Finally, the combination of two different scale factors (small and large) combined with slopes lead to the identification of 10 types of landform classification (WEISS 2001, JENESS 2006).

The Topographic Wetness Index (TWI) is another helpful analyst which is one of the quantitative measures describing the effect of topography on hydrological processes. The TWI indicates the relationship between the size of the area involved in surface water collection, and the value of its slope according to equation:

$$\mathrm{TWI} = \ln\left(\frac{\alpha}{\tan\beta}\right) \tag{2}$$

where:
α – catchment area,
β – slope measured in local cell.

The TWI shows the spatial distribution of moisture in the soil. Also, it shows the level of water saturation in soil based on topographic conditions (SØERSEN at al. 2006). The greatest values of the TWI are reached in areas of large surface water catchment and small slope. Topographically such places are usually very wet, so it could indicate the existence of concave forms (URBAŃSKI 2012).

Results and Discussion

The GIS software (ArcMap, SAGA-GIS) was used for the identification and delineation of concave forms in the test area. The ISOK DTM was the source data. This DTM is derived from ALS data. The scan density was in range of 6 to 12 points/m^2. The final DTM resolution is 1 metre. Declared by the manufacturer the height accuracy of the DTM is 15 cm. So this value has been adopted as the threshold below which all found locations are treated as concave terrain forms. The map with delineated concave forms was developed using tools for the surface terrain analysis (Fig. 4).

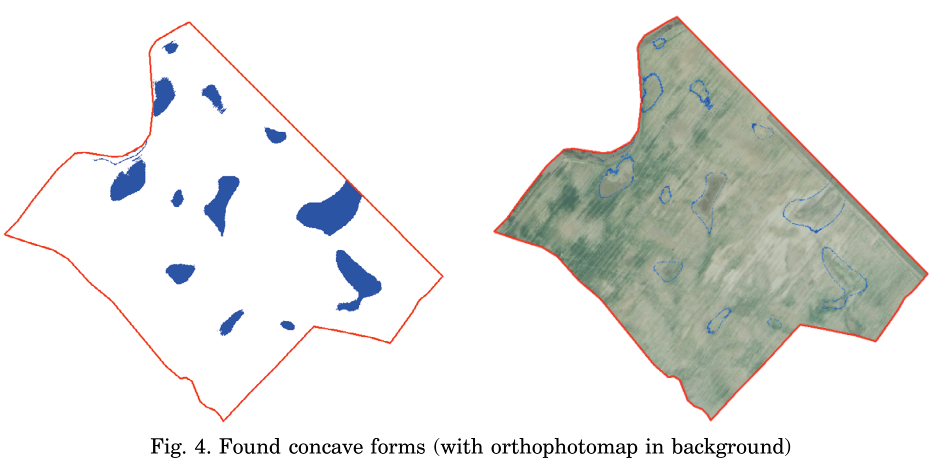

Fig. 4. Found concave forms (with orthophotomap in background)

At first, the TPI index was calculated. The circular shape was used to determine the neighbourhood's average terrain elevation of each DTM cell. Several sizes of radii (scale factor) of the neighbourhood were tested. The large scale (large radius) gave a few large concave features while using a small scale generated a lot of various small forms. An example of different scaled TPI maps is shown in Figure 5.

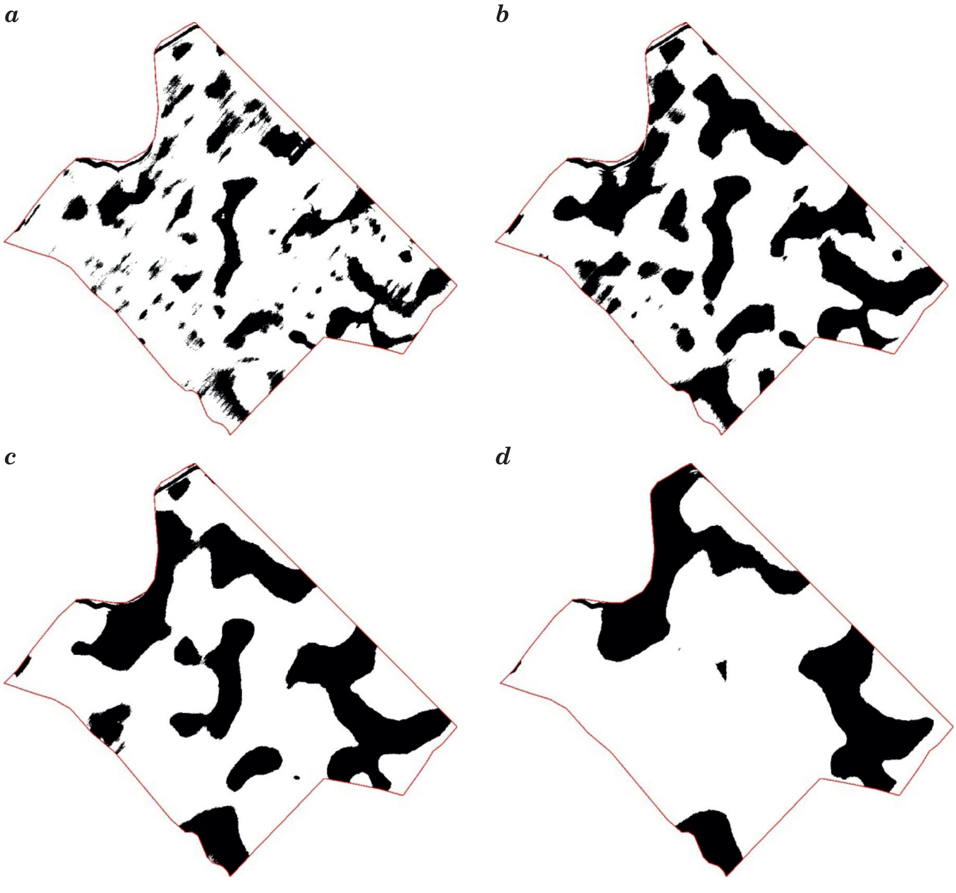

Fig. 5. Low values of TPI index at 4 different scales: *a* – 25 m, *b* – 50 m, *c* – 100 m, *d* – 300 m

Two most appropriate scales (radii) were selected (radius 25 m and 100 m). Using such TPI maps allows to combine small and large forms. In a second step the classification of the land forms were done. The combination of small and large scales gives 10 different types of the landform (WEISS 2001). The main topic of the experiment was finding concave forms. Thus, only such forms were analysed. The previous classification was reduced to forms which are naturally lower than their surroundings. Finally 5 different landforms were qualified as representative. There were: canyons, deeply incised streams, drainages mid-slope, shallow valleys and u-shaped valley. Figure 6 presents chosen landforms combined with previously delineated concave forms.

In additional the TWI index map for the test area was created. Large TWI values could indicate wetness in specific regions which is usually positively

Fig. 6. Selected landforms and delineated sinks

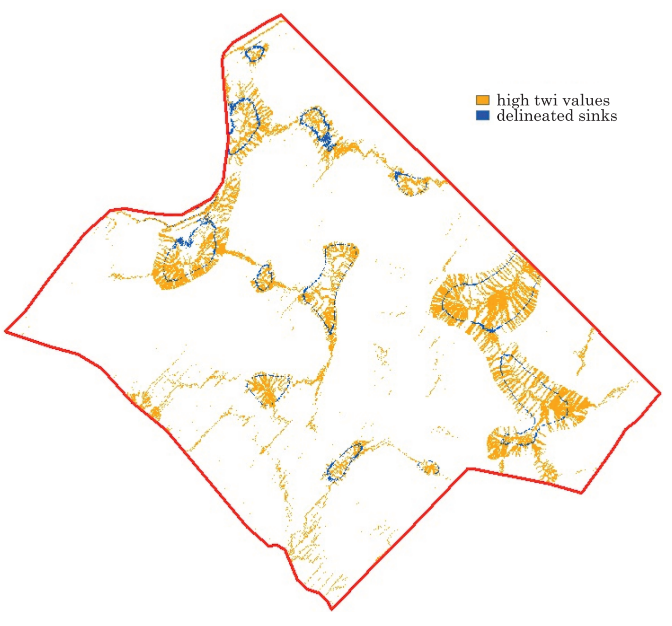

Fig. 7. The TWI highest values and delineated sinks

correlated to the shape of the analysed terrain, a concave form and its higher neighbourhood. The slope around such a depression is always directed inside. In the vast majority of cases such locations are concave forms. If they have a longish shape it often coincides with the direction of the water flow. In this experiment the highest values of the TWI have a similar location as the previously delineated concave objects and concave forms found using the TPI classification. The results are shown in Figure 7.

Conclusion

The precise delineation of concave forms is not an easy task, both in-situ and in the laboratory based on an DTM. We should remember that the correctness of the findings based on a DTM not only depends on its height precision but also on its resolution. The ISOK's DTM is interpolated from a point cloud captured by ALS. Obviously, filtering and classification of the ALS points led to a lower point density as declared by the data distributor. In fact, the density of 4–6 points/m^2 is probably not guaranteed everywhere. The grid is the result of an interpolation. It always approximates the shape of the topographic surface. Accordingly, small landforms could be smoothed. Consequently, they are impossible to be identified on the basis of this data. The results of the experiment show that the DTM of the ISOK project allows finding the boundaries of the concave forms in the tested area. Generally, in most cases the found concave forms have the correct location. However, their borders differ from those found by the TPI landform classifier. Attention should paid to the fact that TPI and TWI classified some regions as concave while the ArcGIS functions did not give any indications. This may mean that the forms are shallower (less than 0.15 m below the surrounding) and thus omitted due to the threshold of the height accuracy of the DTM. The method of searching concave forms based on the DTM can be very useful for every kind of terrain, especially difficult and non-accessible regions. The method has some limitations, among others a not fully reliable border detection. However, it showed that the analysis of the DTM data regarding small and larger land forms can be performed successfully. The ISOK DTM is currently the most reliable and quite accurate data source on the topographic surface of the majority of the Polish territory. It is a good foundation for various analyses. We can expect that through the development of new measurement techniques, hardware and software the DTM will in the future be even more precise which certainly will lead to even better analytical results.

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