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Geo-Information Systems course

at **Lund University**

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GIS and 3-Dimensional Digital Terrain Modeling

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I. Introduction

The main aim of this project is to show, how a paper map can be implemented into GIS software and how it can become a source of data for creating a DTM (Digital Terrain Model), which then can be used for many other purposes.

So far, paper maps are still very common (which means also very important) source of geographic data. There are, however, several problems that have to be solved while using analog maps in GIS. This project will show, step by step, how does this procedure look like, from the very beginning (registering a scanned paper map) to some final results (visualization and analysis).

II. Maps - Models of 3-Dimensional Reality

Maps are often called models of reality. For many years cartographers had to face a very difficult problem: how to show a three-dimensional reality on a flat surface of a map. Despite the natural curvature of the Earth, which is a bit different (and more complex) problem and will not be discussed within this project, there is natural land diversity in elevation. The shape of the ground's surface like hills, valleys, plains, and slopes is often called **topography**.

The representation of topography has always been one of the most challenging tasks for cartographers. First of all, there is a third dimension (height) that varies continuously over space and has to be flattened to a two dimensional map. Moreover, topography has several components, such as height, slope and shape that can be mapped. This resulted in a broad range of mapping techniques that has been invented. Some of most important will be briefly overviewed below. Generally speaking, these techniques were used both to create an effective visual result and a map that can be used for deriving exact values of topographic components. Therefore, the techniques vary considerably in how effective they are visually (imageable) and how quantitative (commensurable). Usually these two components work against each other.

At the very beginning cartographers used to represent mountains as “**sugar loaves**” and whole mountain ranges as ranges of “sugar loaves”. An example of a map using this method shows Figure1.

Figure 1. *Map of Saxtons Hampshire, 1575 (see the close-up in the bottom-left corner for a “sugar loaf” mountain).*

In the very end of 18th Century Major Lehmann, an Austrian military officer, systemized method called **hachuring**. It uses lines of varying width and length to represent slope steepness, drawn in direction of steepest slope. One of the major advantages of this method was ability to represent accurately the steepness of a slope. It had, however, many disadvantages: it was very time-consuming, in the very hilly terrain hachuring lines were so wide and close to each other that it was impossible to represent on a map anything despite the topography. The first known form of this method, giving general location of mountain ranges is called “**hairy caterpillars**” (see Figure 2).

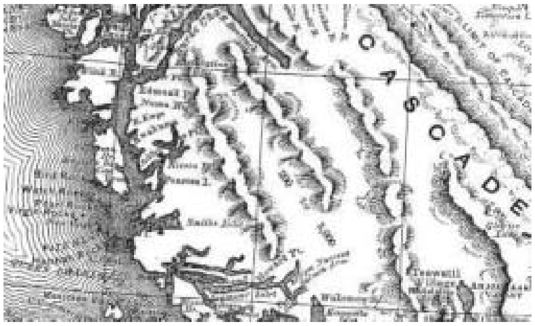


***Figure 2.** An example of a map using "caterpillar" method.*

Nowadays the most common way of representing topography on maps are **isolines** (**contour lines**; see Figure 3), that connect points of equal **elevation** (altitude of the land compared to sea level). For explanation how contour lines are constructed see Figure 4.

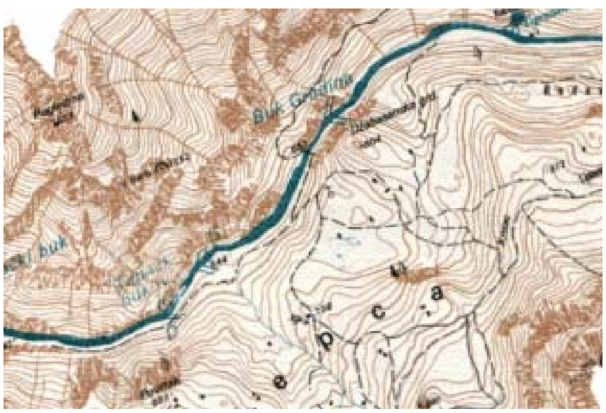


***Figure 3.** Tara Canyon in Monte Negro.*

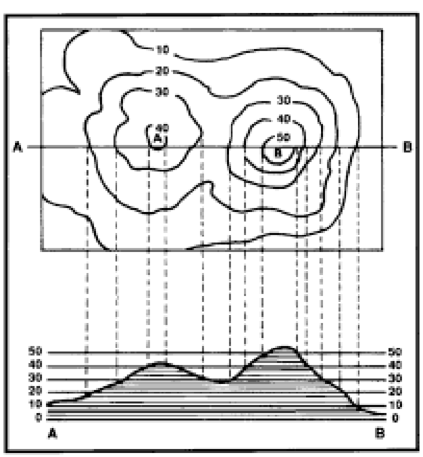


***Figure 4.** Method of constructing contour lines.*

This method has led to other methods being developed. Some of them are shown below:

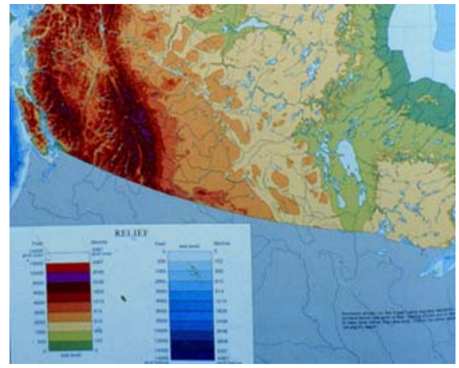


***Figure 5.** Hypsometric tints.*

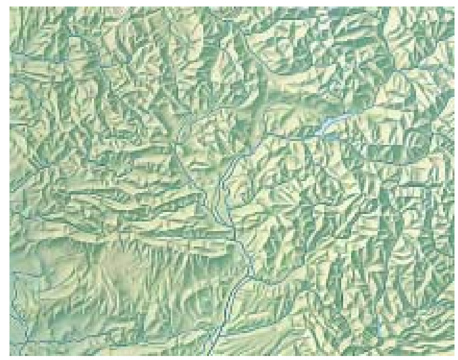


***Figure 6.** Shaded relief (hill shading).*

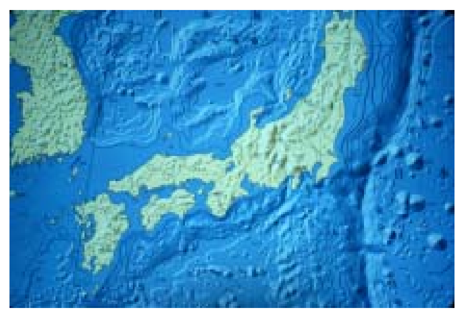


***Figure 7.** Tanaka (relief) contours.*

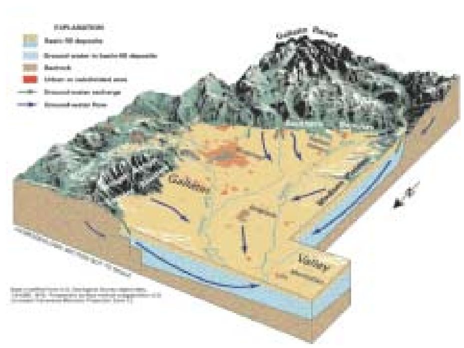


***Figure 8.** Block diagram.*

The end of 20th Century brought major changes in cartography, mainly due to computers and Information Technology. Storing, analyzing and visualization of geographic data became much easier and much more efficient. Despite this, many new possibilities have arisen. Using **GIS software** enables its users to make analysis that were not possible with paper maps (eg. analyze visibility, slope, aspect or automatically create watersheds). Moreover, GIS makes it possible to visualize geographic data in three dimensions. Methods of representing 3D reality in GIS are discussed in next paragraph.

III. Three Dimensions in GIS

There are several ways of representing surface of the Earth in GIS. Since there are two main data structures (raster and vector), there are also same two types of methods using for 3D visualization.

DEM (***Digital Elevation Model***) is raster-based method and generally refers to a regular array of elevations (squares or hexagons). Each cell in the grid has its own elevation value. This term is in widespread use in the USA, but many similar abbreviations are also in use in other parts of the world. **DHM** (***Digital Height Model***) is similar to DEM but less commonly used (mainly in Germany), **DGM** (***Digital Ground Model***) is more focused on the digital model of the solid surface of the earth, while **DSM** (***Digital Surface Model***) refers to the terrain that includes also man-made features (eg. buildings). Generally speaking all those raster-based methods are types of **DTM** (***Digital Terrain Model***), which is more general term used to describe models focusing on digital representation of the terrain. According to US National Center for Geographic Information Analysis (NCGIA): "The term digital elevation model or DEM is frequently used to refer to any digital representation of a topographic surface. However, most often it is used to refer specifically to a raster or regular grid of spot heights. Digital terrain model or DTM may actually be a more generic term for any digital representation of a topographic surface, but it is not so widely used."

TIN (***Triangulated Irregular Network***) is a vector-based method, which treats topographic surface as a surface consisted of number of non-overlapping triangles. The corner of each triangle matches the elevation of the terrain exactly.

This means that a topographic surface is represented by number of triangles, with each triangle face having an approximate slope, aspect, and surface area. The irregularity of the triangles comes from the scattered nature of the (x,y,z) points (triangle corners) used as a background elevation source. A TIN is in this way one of the methods of interpolation, since the elevation of any point on the triangle's continuous surface can be measured.

A TIN can be created from several different data sources: from a set of points (x,y,z), isolines (digitized from a paper topographic map) and from a DEM used as a background elevation source.

As stated above, a TIN is formed by nodes, triangles and edges (see Figure 9). Nodes are locations defined by x, y and z values from which a TIN is constructed. Triangles are formed by connecting each node with its neighbors according to the Delaunay criterion: all sample points are connected with their two nearest neighbors to form triangles (by using this method the triangles are as equi-angular as possible, any point on the surface is as close as possible to a node, and the triangulation results independent of the order the points are processed). Edges are the sides of triangles.

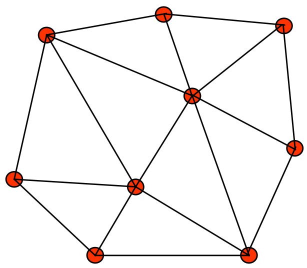


Figure 9. *TIN structure.*

Major advantages of a TIN in comparison with DEM terrain model are:

- ☞ less amount of data and hard disk space is needed,
- ☞ "adaptive resolution": it is possible to use more sampling points in some more important areas (e.g. areas were the topography is more variable or need to be represented in more details),
- ☞ some linear features like roads and rivers can be represented more accurately,
- ☞ TIN uses several methods and input data types (like mass points, soft breaklines, hard breaklines, exclusive polygons) to model a surface more accurately,
- ☞ there are some things such as reservoir generation and flood plain delineation that are only available with TINs.

GIS can also represent 3-D reality in more "traditional" ways that were described in Chapter 2 (e.g. contour lines, shaded relieves, block diagrams). They are, however, often used as a source of elevation data derived from paper maps (contour lines) or as additional methods of improving 3-D visualization (shaded relieves) (see Figure 10).

Figure 10. *DEM with shaded relief.*

IV. Project's step-by-step overview

0. Study area

The project's study area is a small fragment of **Bieszczady Mountains** (see Figure 11). It is one the most beautiful Polish mountain ranges, covering the very south-eastern Poland. The geology dominated by sandstone and shale base rocks is typical for the Carpathian Range. The area is 65% forested. A large proportion of former agricultural land is abandoned and under various stages of secondary succession, up to 50 years old. There are approximately 700 species of vascular plants and 284 species of vertebrate fauna including all large European predators (wolf, brown bear, lynx, wildcat), and a number of herbivorous species like European bison, red and roe deer, moose and wild boar. The region has a very low population density (5-10 people/sq. km).

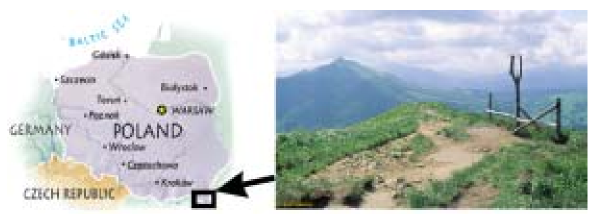


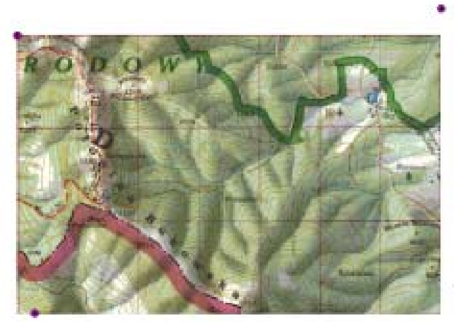
Figure 11. *Location of Bieszczady Mountains.*

The unique character of the Bieszczady Mountains is covered by a number of National and Landscape Parks. These include Bieszczady National Park, which covers the most important and the most beautiful landscape of Eastern Carpathia. The highest peaks in the Polish Bieszczady are Krzemień (1,335m. above sea level), Halicz (1,333m. above sea level) and Tarnica (1,346m. above sea level).
A characteristic of Bieszczady is the large, high grass mountain meadows, called mountain pasture. The largest of them are Połonina Wetlińska (1,253m. above sea level), and Połonina Caryńska (1,297m. above sea level). Some of the attractions of

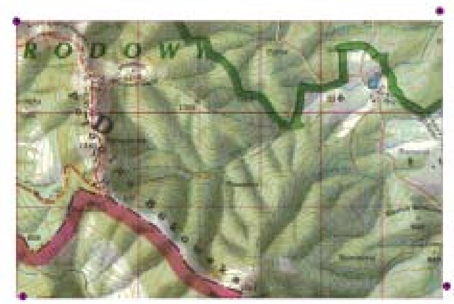
the Bieszczady Mountains Pastures are the frequent outcrops, on the higher peaks, of comp-shaped patches as well as the stone scree on the mountain-sides. The biggest and the longest stone comb is located in Krzemień, also known in the past as Hrebień.
Bieszczady Mountains are one of the wildest and most well preserved natural areas in Poland.

1. Registering a scanned map in ArcView

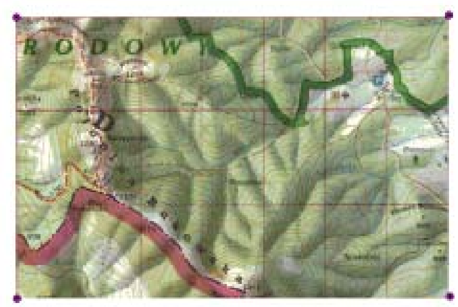
The main aim of this project meant to be working on a DEM but soon it became clear, that the first step would be the most difficult. The source map was taken from the Internet map server (http://mapy.mk.cvut.cz) and had no specified projection. The only clue was a grid (parallels and meridians with known coordinates) and ellipsoid (WGS 84). The only way to import this map to ArcView was to “guess” the projection or to choose the most suitable one.
First, a table with four checkpoints had to be done. Each point stand for each corner of the map and had specified coordinates derived from the grid. These points were added to ArcView as an event theme, converted to shapefile and reprojected to a few possible projections. For this project UTM-1983 projection with central meridians at 18, 21, 22.5, and 24°E was checked, as most probably used for creating the source map (Poland is situated between UTM Zone 33 and 34). For each case different “world file” had to be created. The results of these adjusting processes are shown in Box 1.
Finally, 22.5°E central meridian was chosen. The approximate mean error (distance between checkpoints and map corners) was 23 meters, while pixel size in map units was 15,38 m. This result was considered good enough to proceed and start digitizing process.



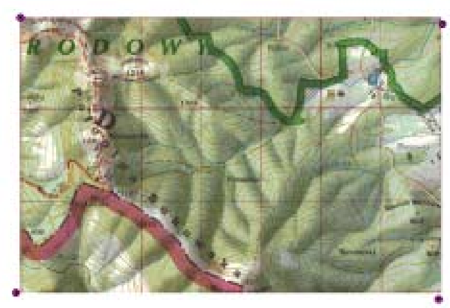
☝ central meridian: 18°E



☝ central meridian: 21°E



☝ central meridian: 22.5°E



☝ central meridian: 24°E

Box. 1. *Results of adjusting a scanned map to UTM-1983 projection with different central meridians (see four control points).*

2. Digitizing

Digitizing process was done manually. Each contour line was digitized and proper elevation was attached to the attribute table. During digitalization a **Freehand Drawing Tool extension** could be uploaded.

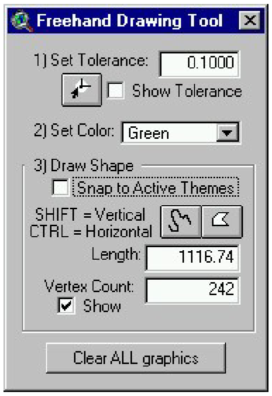
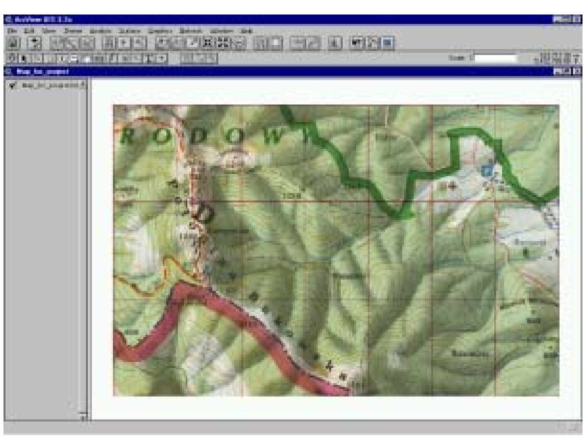


Figure 12. *Freehand Drawing Tool dialog.*

This extension contains a dialog with tools that allow the user to draw lines or polygons freehand. The dialog allow the user to select a color for the line and to specify a tolerance so multiple vertices are not created close to each other. It also enables creating horizontal and vertical lines, setting the size of the line graphic and snapping to features of all the active themes.
Two different line layers were created while digitizing: one with contour lines and one with rivers (see Box. 2).



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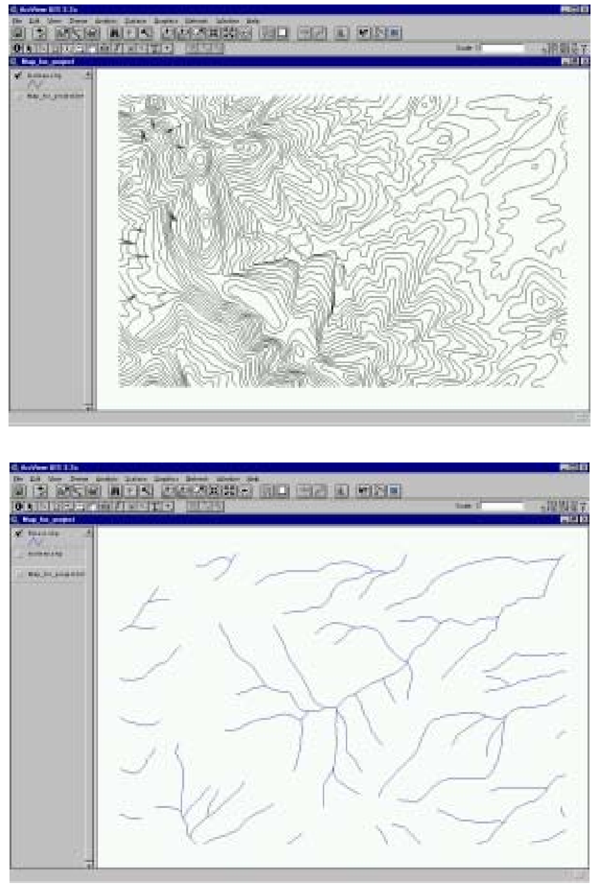
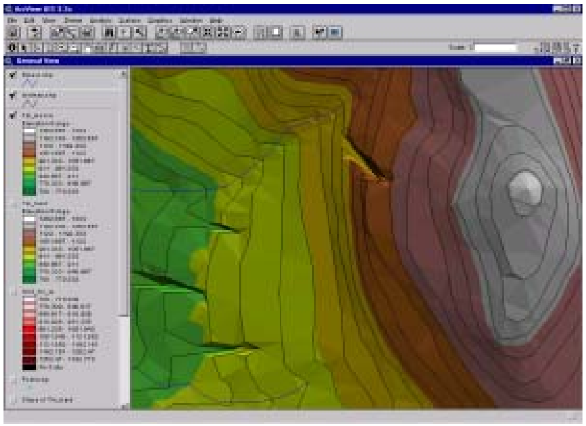


Box 2. *Digitizing contour lines and rivers from a scanned map.*

3. Interpolation, Creating TIN

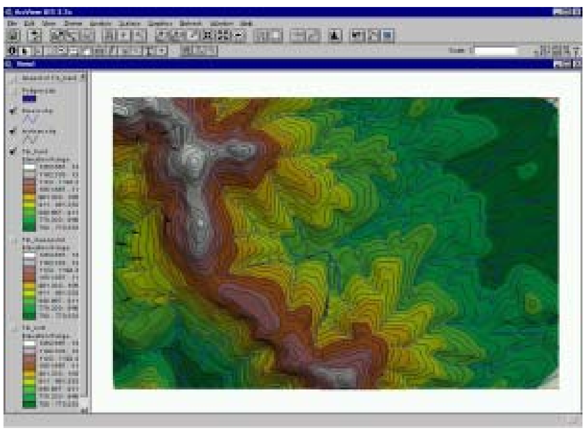
Next step was to create a TIN coverage from contour lines. This requires a **3D Analyst extension**. This extension extends ArcView to support surface modeling and 3D visualization.
As mentioned in Chapter 3, TINs can be generated from points, polygons and lines.
Hard Breaklines are lines, which have an elevation value connected to each vertex. The TIN is forced to triangulate to that edge, such as a mountain peak or ridge.
Soft Breaklines are lines which do not have elevation values, but which the TIN uses to triangulate on in the case of a river trickling down a mountain.

Mass Points are points which are used to build the surface; all have elevation values but there are no lines to force the triangulation.
Hulls / Lake Surfaces – Hulls are the bounding box of the triangulation. Lake surfaces are polygons, which have an elevation; the TIN ensures the lakes are flat at specified height. When a TIN is created, mass points become nodes of triangles, while breaklines and exclusion polygon boundaries become triangle edges.
For this project contour lines were used as hard breaklines and rivers as soft breaklines.
Results of creating a TIN are shown in Box. 3.

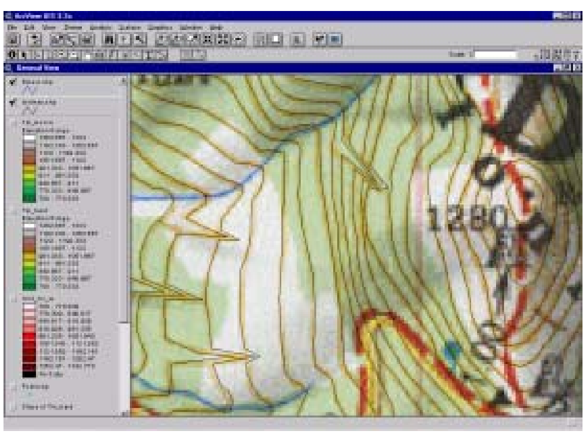


☝ Close-up of TIN (contour lines as hard breaklines, rivers as soft breaklines)

Box 3.



☝ A TIN created from contour lines



☝ Close-up of original map and digitized rivers and contour lines

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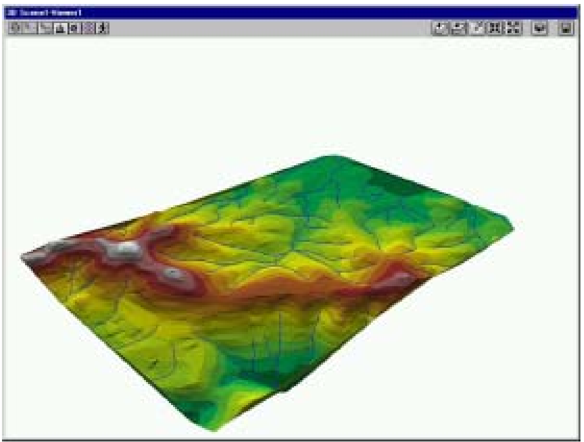
4. Visualization in 3D

While the TIN is created and 3D Analyst extension uploaded, it is possible to present the surface model in 3D. It will later be used to visualize results of some spatial analysis. It is also possible to add to the 3D view other themes (layers), e.g. rivers and drape raster images over TIN. Moreover, in view properties user can define such parameters like vertical exaggeration factor, or sun position (azimuth and altitude).
Some transformations of a 3D view are presented in Box. 4.



TIN and rivers with hill shading

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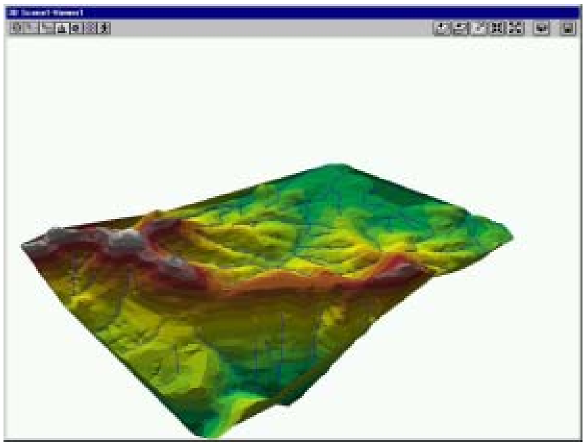
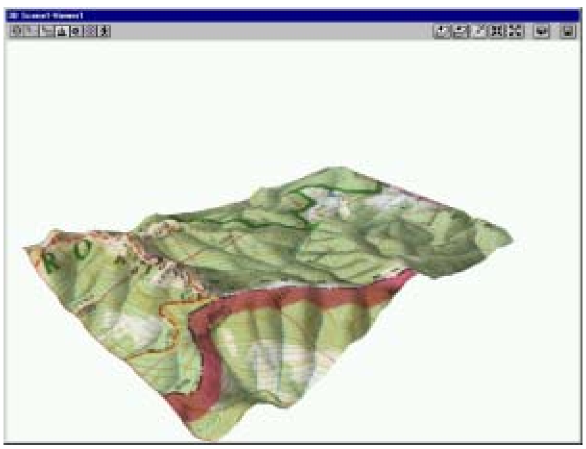


TIN and rivers with hill shading (vertical exaggeration factor=2)



Original map draped over TIN with hill shading (vertical exaggeration factor=2)

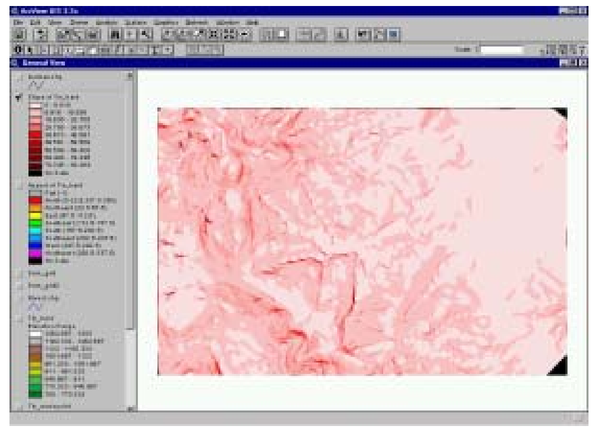
***Box. 4.** Different 3D view properties*

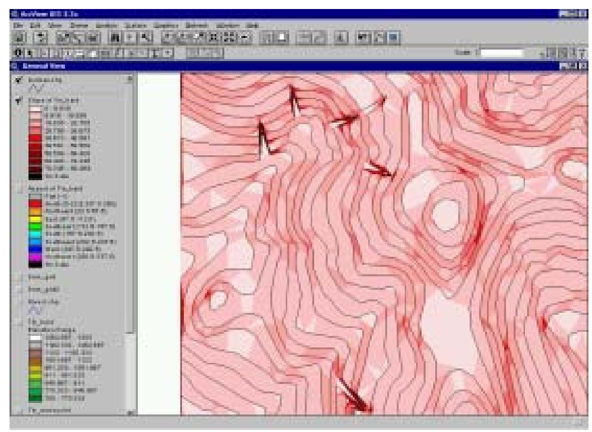
5. Spatial Analyses and Their Usability with Spatial Analyst extension

ArcView Spatial Analyst provides a range of spatial modeling and analysis features. This extension allows user to create, query, map, and analyze cell-based raster data and to perform integrated vector-raster analysis.

- Slope

Slope is a measure of change in surface value over distance, expressed in degrees or as a percentage. For example, a rise of 2 meters over a distance of 100 meters describes a 2% slope with an angle of (approximately) 1.15°. Mathematically, slope is referred to as the first derivative of the surface. The elevation data is derived and recalculated from the TIN, while the result is stored as a raster data. An example of this analysis is shown in Box 5.





***Box 5.** Slope analysis.*

Slope analysis is performed for many purposes: urban planning, architecture and buildings design, agriculture, recreation, natural hazards and risk modeling. Land use very often depends on the slope, e.g. hilly terrains cannot be cultivated without terracing.

- Aspect

An aspect is the compass direction toward which a slope faces, measured in degrees

from North in a clockwise direction. Value of –1 is usually assigned to flat areas. This type of surface analysis can be performed for the same reason as slope analysis. For example some plants can be grown only on sun-faced sides of hills, or while planning your new house you'd like the living room to be faced to the west, so that you can enjoy scenic sunsets every evening!
An example of this kind of analysis shows Figure 13.

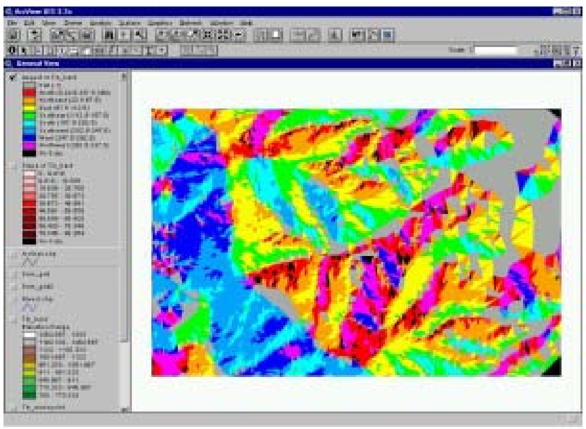


Figure 13. *Aspect analysis.*

- Profile Extracting and True Distance Measuring

One of the main aims of this project from the very beginning meant to be calculating real (topographic) distance for a user-drawn line.

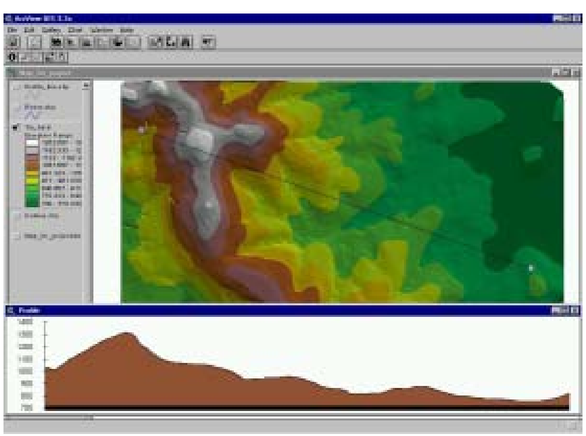


Figure 14. *Profile extracting.*

This useful measurement can be easily done with Profile Extractor 6.0 extension. It extracts cross section profile from a DTM/TIN. The user can draw cross section line (polyline, rectangle, circle or polygon), select existing one, move selected line or it's ends or rotate a line around it's middle point. The profile is drawn into a chart.
This analysis can be very useful e.g. for hikers, who want to know how long a true distance of their hike will be, or what the sloppiness, maximum and minimum altitude of this way will be.

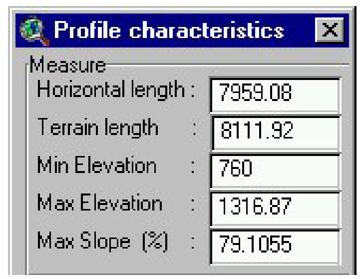


Figure 15. *Profile characteristics.*

- Visibility

ArcView Spatial Analyst extension enables also analyzing visibility from a specified point. First, a TIN had to be transformed into a GRID elevation data source. The result is a wished, a grid with cells divided into two classes: 1 for areas that are visible from the selected point and 0 for areas non-visible. This grid can be draped over GRID or TIN model in 3D (see Figure 16).

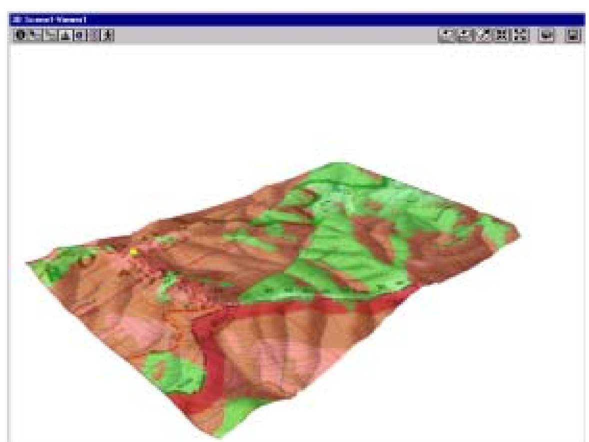


Figure 16. *Analysis of visibility. A small yellow dot is an observer's position, while green areas are visible from that place.*

The result is, however, not very reliable, since no height could be prescribed to the observer.

- Sloppiness of rivers

Calculating the steepness of rivers is a very simple but very often-performed hydrologic analysis. It can be done with the LineSlope Analyst Extension. The extension calculates percent slope for each line in a line theme, based on a grid or TIN Z value theme.

As a result next field is attached to the rivers' theme attribute table with calculated steepness value. Then, all rivers can be classified and presented on a map according to their percent slope (see Figure 17).

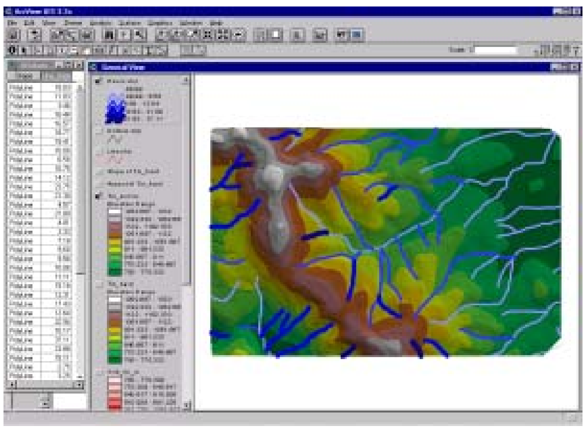


Figure 17. *Rivers classified by steepness (see the attribute table on the left).*

6. Import to IDRISI

In order to perform more sophisticated surface analysis it is useful to move to IDRISI software. It gives a better description of methods that are used as well as more detailed documentation for the results of performed actions. For this project IDRISI will be used only for different interpolation methods and "evaluating" them by slope analyses.

First, the vector file containing digitized contour lines was imported to IDRISI. During this process, IDRISI reads only first field from the vector file attribute table and attaches it to newly created VCT file. As a result, contour lines had ID's as values. Therefore, it was necessary to assign to each line its original elevation value (see Figure 18).

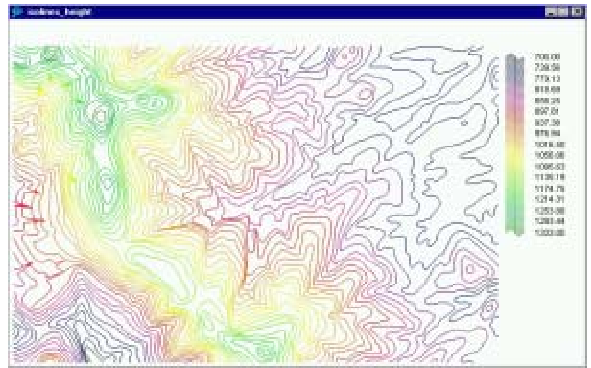


Figure 18. *Contour lines imported to IDRISI.*

The next step was to convert contour lines into points (Figure 19). This new vector file could be now interpolated to a DEM. For this project a few different interpolation methods were used.

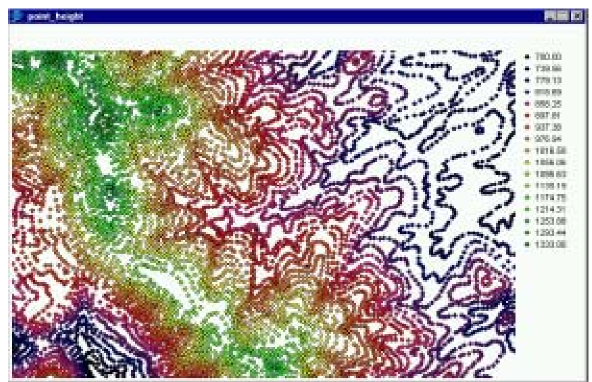


Figure 19. *Points derived from contour lines.*

First, the Inverse Distance method was used. Inverse distance weighted interpolation determines cell values using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance. The surface being interpolated should be that of a locationally dependent variable.

IDW lets the user control the significance of known points upon the interpolated values, based upon their distance from the output point. By defining the higher value for power nearest points will have greater influence. Thus, nearby data will have the most influence, and the surface will have more detail (be less smooth). Specifying the lower value for power will provide a bit more influence to these of the surrounding points which are a little farther. A common value is 2. The output DEM created with IDW (to power 2) is shown in Figure 20.

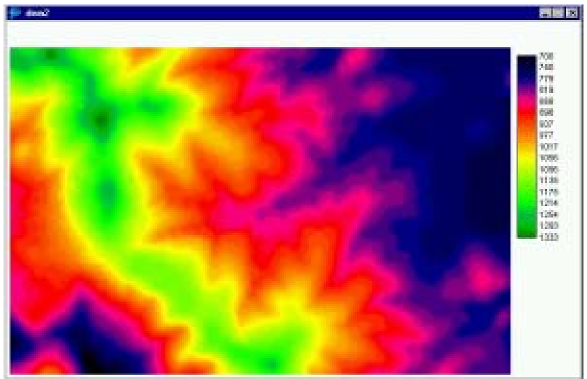


Figure 20. *DEM made with Inverse Distance Weighting (six point search radius).*

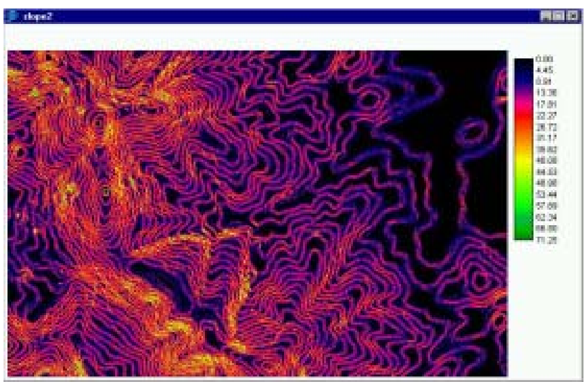


Figure 21. *Slope analysis.*

Figure 21 shows the result of slope analysis made on this DEM. The highest values are along former isolines while areas between them are considered to be flat (which is far away from reality of course).

In order to try avoiding “terraced” DEM other actions had to be performed. One possibility was to reduce number of points and acquire more randomized points distribution.

Point generalization function was used to generalize vector point data. Points were thinned based on a user-defined tolerance distance specified in reference system units (in this case 100m distance was chosen). The first point of the vector file is taken as the starting point. Any other points that are within the specified tolerance distance to the first point are deleted from the file. The next remaining point is then taken as the point from which distances are measured. This continues until the entire file has been processed. This generalization process resulted in a new, randomly distributed set of sample points (see Figure 22).

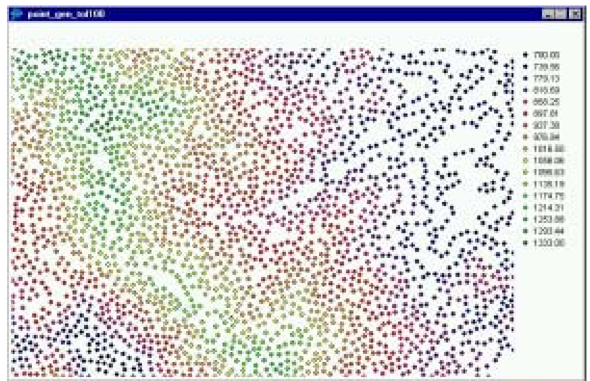


Figure 22. *Randomly distributed points after generalization.*

Although this result seemed to be good (randomly distributed points) slope analysis uncovered that DEM interpolated from this set of points is still terraced (see Figure 23).

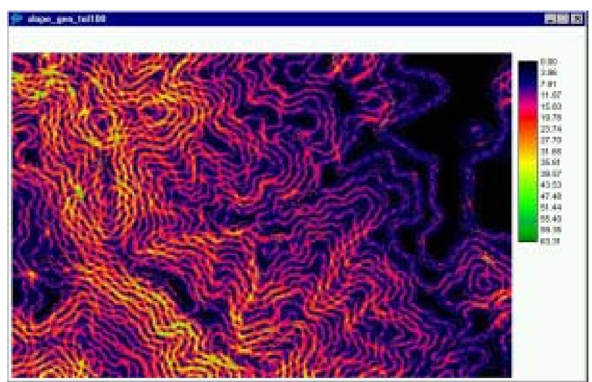


Figure 23. *Slope analysis.*

This comparison led to a conclusion, that what influences a DEM mostly, is an interpolation method and the points’ nature. Points derived from contour lines, although

distributed randomly, have still the same values as isolines and there are no points between former contour lines.
Close-up of this DEM (Figure 24) shows another problem: a bull's eye effect. It means, that each point has a very strong influence on its neighborhood. This could be one of the reasons, why the DEM was terraced. One way of dealing with this could be decreasing the weight of exponent in IDW.

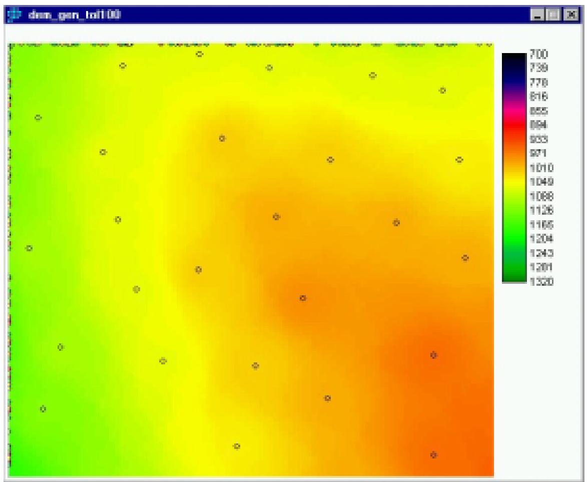


Figure 24. *Close-up of DEM (bull's eye effect). Small black circles are sampling points.*

Therefore, a new IDW interpolation (to the power of 1) was performed. The "bull's eye" effect was significantly reduced, although slope analysis of this DEM was also very poor.
For this project some other interpolation methods were used. Quadratic and cubic trends didn't fit the reality at all, while Thiessen polygons method resulted in too big polygons, which were flat while slope's steepness was significant only on polygons' borders.
Finally, a TIN was created. In order to perform slope analysis raster surface (based on TIN and vector points' layer) had to be created first. The result of this analysis is shown in Figure 25.

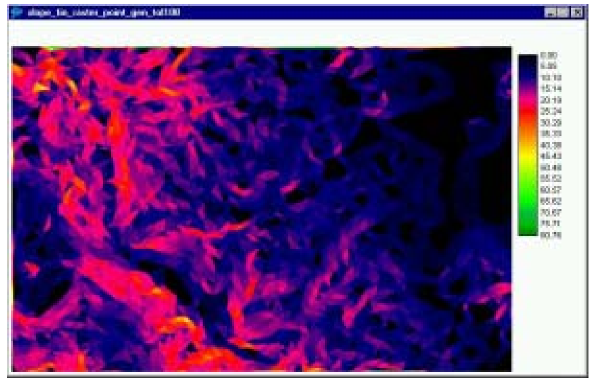


Figure 25. *Slope analysis of a DEM created from TIN.*

V. Conclusions and Problems for Further Studies

This project was limited to one-week work. During this work several questions had been left without answer and many important problems occurred, that should be solved, discussed or reviewed at least.

The continuation of this project could lead to the answer for these questions:

- How does each extension used for this project work?
It is of great importance to understand exactly, what algorithms and mathematical operations are performed while using each function. For instance there are several methods of calculating terrain length of a line. Which algorithms are used by Profile Extraction extension? In order to get accurate and reliable results it is important to understand differences between all possible methods. This kind of knowledge is also crucial for realizing and measuring the accuracy of results.

- Which method of interpolating DTM/TIN from contour lines should be chosen?

Depending on the nature and distribution of sample points there are several ways of interpolating a DTM and TIN. While interpolating contour lines points' distribution is usually very bad (no points are between contour lines, which influences interpolation heavily and often led to "terraced" DTM). In order to get reliable results it is necessary to randomize sample points (which was done within this project) or choose different interpolation method (e.g. Modified Shepard's Method that uses an inverse distance "least squares" method and reduces the "bull's-eye" effect around sample points).

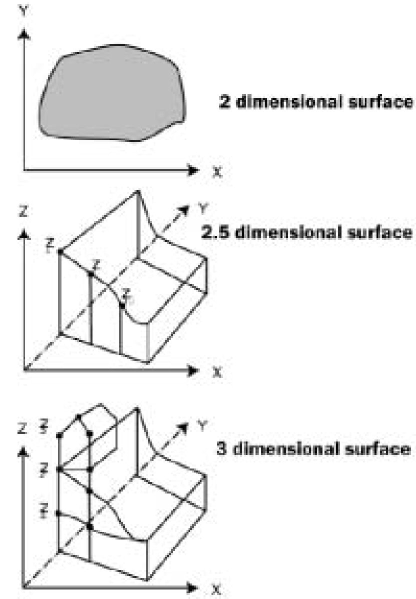


Figure 26. *2.5 vs 3-Diemensional reality*

- What other kinds of analysis can be done with a topographic map as a background?

This project showed how a tourist topographic map can be used for different purposes. This proves that GIS can widely extend possibilities of handling traditional geographic data sources (maps). Processing the same source of data with GIS can led to many different and new measurements, analysis and results. It can also improve and fasten traditional, simple measurements (like calculating area or distance) as well as extend them to 3D measurements. Within this project only a few analyses were performed. Other possibilities could be also reviewed.

- Is a DEM 3-dimensional model in fact?

A DEM (or DTM in general) can represent only one elevation value for each point on its surface. But reality is different. Many natural (e.g. cliffs) and man-made (e.g. bridges) features have several values of elevation (z) that can be attached to on place (x, y). Normal DTM can't handle this problem. Many authors call such GIS models 2.5-Dimensional. This problem can also be discussed in more detail.

- How accurate are the results?

Evaluation of results is an inherent and one of the most important parts of each GIS project. Very often it enforces fieldwork (e.g. GPS measurements) or comparing the results with other data. Depending on the nature of source data and performed analyses there are many different ways of evaluating the results. This problem should also be discussed more deeply.

Summing up, it is obvious that GIS is a powerful tool for handling both digital and analog data. Even a paper, topographic map implemented into GIS can become a background for different (and sometimes even complex) analyses. One of the main aims of this project was to show some of these possibilities.

GIS offers both efficient ways of measuring and analyzing data as well as effective methods of representing them. Does it mean, that this cartographers' problem is about to be solved…?

Software used for the project:

- **ArcView GIS© 3.2a** (extensions: 3D Analyst, Spatial Analyst, Freehand Drawing Tool, Profile Extractor, LineSlope Analyst)
- **Idrisi32©**

Figures' sources:

- Figure 4. http://www.uml.edu/tsongas/activities/read_map.htm
- Figures 5 and 7. http://www.gis.unbc.ca/webpages/start/geog205/lectures/reliefdepiction/reliefdepiction.html
- Figure 26. http://www.sfu.ca/gis/web_354_new/icons/lec_10_interpolation.pdf
- Figure 6. http://www.reliefshading.com/examples/swisstopo.html
- Figure 8. http://water.usgs.gov/pubs/circ/circ1217/html/importance.html
- Figure 10. http://home.san.rr.com/bwagner/DEM_Reader.html

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