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"A methodology for creating analytical hillshading by combining different lighting directions".

A METHODOLOGY FOR CREATING ANALYTICAL HILL-SHADING BY COMBINING DIFFERENT LIGHTING DIRECTIONS

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ABSTRACT

The present study examines ways of creating analytical hill-shaded images by applying more than one light sources, in order to eliminate, at a certain degree, two deficiencies present in single lighted hill-shaded images. The first deficiency is related to the insufficient representation of the total number of relief formations, due to many different main massif directions in mountainous terrains and the second one to the existence of deep dark shading tones, which make difficult either to detect the slight relief changes, or even to legibly read the superimposed cartographic symbols. An initial hill-shaded image is generated by applying a north-west light direction and is partly replaced by the enhanced weighted combination of the shading images derived from certain other lighting directions, where the amount of partial replacement depends on the incident angle. This methodology aims to achieve a more balanced result of hill-shading, in such a way that the perception of the initial optimal lighting is preserved, as well as, the major relief forms in all directions are revealed or even sharper local details are enhanced.

1. INTRODUCTION

Hill-shaded images for cartographic use are usually produced by considering the light coming from north-west, as this has been visually approved to help all map users, experienced or not in map reading tasks, to immediately and accurately perceive the forms of earth's surface relief. This condition is deeply rooted in the hill-shading process, due to subconscious, positive understanding of graphic elements under upper-left light in our everyday experience (1).

Apart from the traditional north-west oriented light, other alternative lighting directions from west or south-west might be utilised for better shading results, when the dominating slopes of the portrayed area are facing to north-south or to northwest-southeast. The decision for the optimal direction should depend on determining which one intersects the dominant direction of ridges and valleys diagonally (1). Besides that, the idea of using south lighting on three-dimensional shaded maps of the northern hemisphere has been strongly supported by some cartographers (1), who were mostly concerned about the clear presentation of earth's surface covering, than the accurate perception of the relief.

Scepticism arises from the fact that, a strict adherence to only one, optimal light direction for the total geographic area of the map, would be rather difficult to accentuate the total number of the forms of terrain that exist in the portrayed area, lying along several main directions. This is true, either speaking for huge mountain chains or pointing at the smaller, local relief details. Light direction adjustment is a method that partly deals with the problem, by optimising the portrayal of relief details for those directions of the surface that face the light (1). But still, entire sides of ground formations are kept improperly or not at all lightened, leading to optical confusion and indistinct perception of the underlying relief information or other superimposed cartographic symbols. In larger scales with more detailed relief, the above phenomena acquire more attention, as steeper slopes occur and the variability of aspect is higher.

Mark introduced the idea of combining shaded-relief images illuminated from four basic directions: north, north-west, west and south-west (3). The resulted, multi-directional hill-shading image emphasises not only the structures of the mapped surface area that receive illumination obliquely, but also those that are illuminated along the structural grain (2). This technique produces more detail in specific areas of an image that would either be illuminated by direct light or left in darkness by a single-source illumination. Jenny, in a relevant study (4), introduced an interactive approach for analytical relief shading by developing tools that enriched the analytical presentation with characteristics similar to those existed in manual produced maps of the past. He combined aspect-based with diffuse reflection shadings, as well as, supplemental bright grey tones in flat areas with aspect based shadings, applying appropriate functions. Such an implementation increases the quality of relief presentation, especially in cases where there is a strong need for the combination by the means of blending of the intermediary raster datasets.

In the present study, a methodology is introduced aiming to resolve the problems generated by the diversity of relief formations directions in relation to the application of a

single lighting source and of the existence of very dark tones. Four shaded relief images are generated each one illuminated from a different direction, and are integrated into one single final image using weights, calculated on a cell by cell basis, derived from a function of the local aspect. The combination of these two products leads in a multidirectional shaded relief image, which is the final outcome. The paper is structured as follows: in section 2, a detailed description of the introduced method is given; in section 3, two case studies are presented; the obtained results are discussed in section 4; and finally, some first concluding remarks are presented in section 5.

2.   DESCRIPTION OF METHOD

The first step of the whole process is based on the calculation of the initial hill-shaded image $[H_{initial}]$ from an available digital elevation model (DEM). The optimal direction of light (expressed with azimuth and slope angles) is selected, in order to represent the dominant relief forms of the portrayed area in the best way. This can be done either empirically or by producing statistical results for the values of azimuth and zenith angles, which can be calculated from the DEM.

The second step is the production of four separate hill-shading images with light sources coming from four different directions, which are then combined into one, multi-directional image using weights. For all of these four separate hill-shaded images, the elevation angle of light direction is the same one used for the initial hill-shaded image. The change in the direction of the light is only due to the change in azimuth angle, and specifically due to the use of four basic azimuth values for north, north-west, west and south-west aspects. Counting clockwise from the north, the values of these four azimuth angles are: 225°, 270°, 315° and 360°, respectively. The raster datasets for the hill-shaded images are symbolised as: $[H_{225}]$, $[H_{270}]$, $[H_{315}]$ and $[H_{360}]$, while the weights are: W_{225}, W_{270}, W_{315} and W_{360}, respectively. The value of each of four weights is ranging from 0 to 1, while their sum is be equal to 1. The final, multi-directional hill-shaded image, symbolised here as $[H_{MD}]$, is calculated using the following expression:

$$[H_{MD}] = W_{360} * [H_{360}] + W_{315} * [H_{315}] + W_{270} * [H_{270}] + W_{225} * [H_{225}]$$

The calculation of weights at this point is based on two different approaches and that is the reason why two separate models of hill-shading are presented here, producing different quantitative and qualitative results. In the first model, each weight has one single, global value for its relative hill-shading image. This value depends on the percentage of the areas that face towards the light direction used for the hill-shaded image. Also, cells that

represent flat areas and do not have significant slope value should be excluded. In order to carry out this analysis, raster datasets with the integer values of azimuth and slope angles of the study area are produced from the DEM, which are then properly combined using zonal analysis (see Figure 1). More specifically, four zones with azimuth ranges of 45° on either side of each main lighting direction –north, north-west, west and south-west– are combined with slopes greater than 10°, and the final outcome is the totals of pixels that fulfil both criteria in each zone, N_{225}, N_{270}, N_{315}, N_{360}. The weights are then calculated using the following formula:

$$W_i = N_i / N_{total}, \text{ where: } i = 225, 270, 315 \text{ and } 360 \text{ and } N_{total} = \text{sum of } N_i.$$
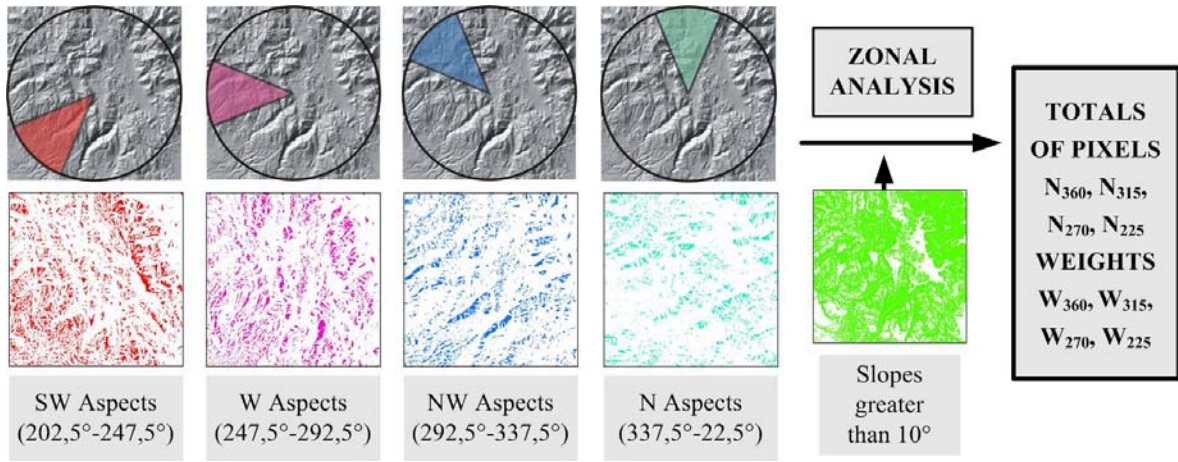

Figure 1. Global weights for multi-directional shading based on statistics of aspect

In the second model of multi-directional hill-shaded image, the weights of the component shading images are defined on a cell-by-cell basis, as a function of the local aspect angle, as follows:

$$[W_i] = \frac{[cos([Aspect] - i) + 1]}{2} * \frac{1}{\sum [W_i]}, \text{ for } i = 225°, 270°, 315° \text{ and } 360°.$$

The aspect angles' raster dataset *[Aspect]* used here is derived from a smoothed DEM and the produced four new raster datasets *[Wi]* contain the weights for the corresponding component hill-shaded images with light coming from north-west, west, south-west and south directions (see Figure 2).

According to the above function, the value of each cell of *[Wi]* becomes maximum when the aspect value is equal to *i* and minimum when they differ by 180°, while values between 0 and 1 occur in all other cases. This means that those cells of the surface that look towards *i* will have a greater weight value than the others, letting us to enhance the participation of these specific cells in the final combination and keeping the contribution of

the rest of cells in an relevant scale. Furthermore, the usage of this function helps to avoid negative values.
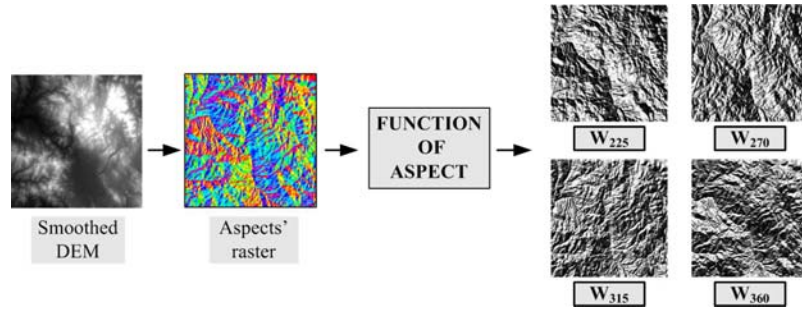

Figure 2. Cell-by-cell weights for multi-directional shading depending on aspect

At the last step -common for both models- the products that come out of the previous two steps are merged, that is the initial hill-shaded image and the multi-directional shading. This merging is made by the means of blending the two corresponding raster datasets, in order to form the final enhanced hill-shaded image, *[H_{final}]*:

$$[H_{final}] = [W_{in}] * [H_{MD}] + [(1-W_{in})] *· [H_{initial}]$$

The blending is controlled by another weight factor ranging from 0 to 1, related to the local incident angle of light, using the following equation:

$$[W_{in}] = sin^2 [i]$$

In this way, the closer to 90º the incident angle gets, the more dominant is the role of multi-directional hill-shading in the final image. The necessary raster dataset *[i]*, containing the local incident angles, is derived from the DEM with applying the following equation:

[i]=cos(Slope_{Light})*[sin([Slope])]*[cos([Aspect]-Aspect_{Light})]+sin(Slope_{Light})*cos([Slope]),

where *Slope_{Light}* and *Aspect_{Light}* are the slope and aspect angles of the light direction assumed for the initial hill-shading.

The local incident angle of light is the angle between the vector of light direction −assumed for the initial hill-shaded image− and the vector of local normal of relief surface (2). When it gets close to or more than 90°, the shading tone becomes very dark or totally black, meaning that the surface gets very small amount or no light at all. One of the scopes of the present study, as described earlier, is to enlighten these dark areas of hill-shading; that is why the incident angle is the controlling factor towards this effort. The other aim of the study is to amplify the presented relief alterations or even bring out new details, which is accomplished with the use of multi-directional shading.

3. CASE STUDIES

The models described above in section 2, are tested on two different geographical areas, with available digital elevation models having different spatial resolution. The first test area is located in Greece, in central Peloponnesus region, west to the city of Tripolis in the county of Arkadia, and its centre is at 22º12´E, 37º34´N. The DEM is produced by interpolating 20-meter contour lines, digitised from a 1:50.000 scale map, published by the Hellenic Geographical Military Service, and it covers an area of 27.40 x 37.85 km^2, with a 25-meter grid. This area contains mountain Menalus and the range of heights is from 331 m to 1987 m. The second test area is in U.S.A., in Washington State, north-west to the city of Seattle, while its centre is at 123º26´W, 47º56´N. The DEM is downloaded from the webpage of Geomorphological Research Group of the Department of Earth and Space Sciences at the University of Washington, and it covers an area of 9.41 x 13.95 km^2, with a 10-meter grid. It is part of mountain Angeles and the range of heights here is almost the same with the previous test area, from 356m to 1968 m. The two test areas are illustrated in Figure 3.
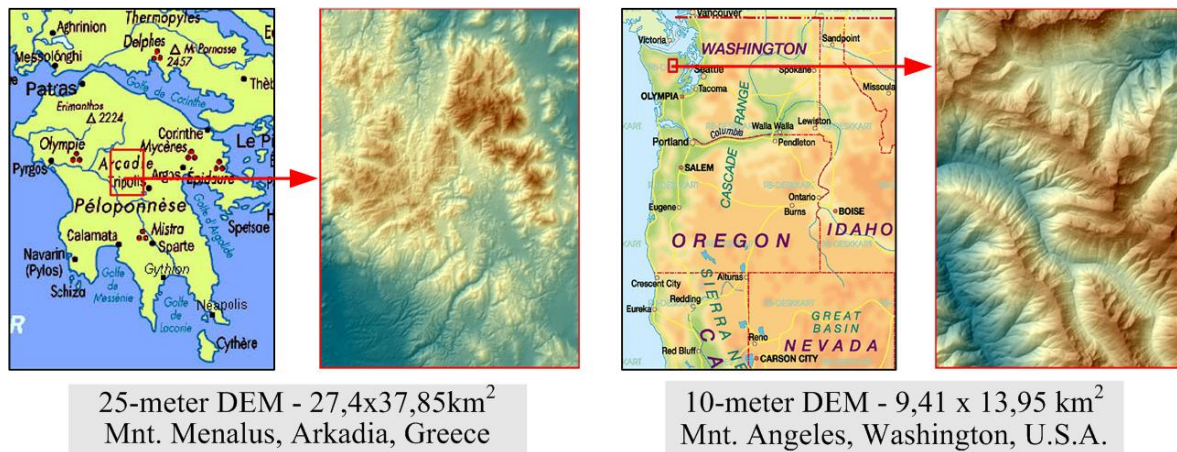

25-meter DEM - 27,4x37,85km^2
Mnt. Menalus, Arkadia, Greece

10-meter DEM - 9,41 x 13,95 km^2
Mnt. Angeles, Washington, U.S.A.

Figure 3. Test areas "Arkadia" (left) and "Washington" (right)

The calculations for the tests are carried out in the GIS software *ArcGIS* of E.S.R.I. The conceptual planning of the two presented models is organised in *ArcMap* environment under *ArcToolbox* module, a doc able window which supports multi step workflow via *Modelbuilder*. The developed *toolbox* contains the two basic models to perform all necessary GIS operations on the selected DEM datasets and return an output dataset with the final hill-shaded image. This way, the process is totally automated and several tests can be done in order to fine-tune the procedures of the models, document the processing steps

(workflow), re-run the analysis to experiment with different parameters to see how results are affected, and finally achieving better results for the study tests.

The images produced from the three steps of each of the two models are shown in Figures 4 and 5, as calculated for test areas "Arkadia" and "Washington" respectively. The assumed light direction for the initial hill-shaded image is the standard north-west direction, where the aspect angle (azimuth of the light source) is 315º -as aspects' origin in *ArcGIS* is at the north direction, counting clockwise- and the slope angle (altitude of the light source) equals 45º. For the first model of multi-directional shading using global weights, the values of weighs are the following:

	W_{225}	W_{270}	W_{315}	W_{360}
Test area "Arkadia"	0.23	0.27	0.24	0.26
Test area "Washington"	0.34	0.19	0.20	0.27

| Initial hill-shading | Multi-directional shading w/ global weights | Blended shading from initial and global weighted multidirectional | Multi-directional shading w/ cell-by-cell weights | Blended shading from initial and cell-by-cell weighted multidirectional |
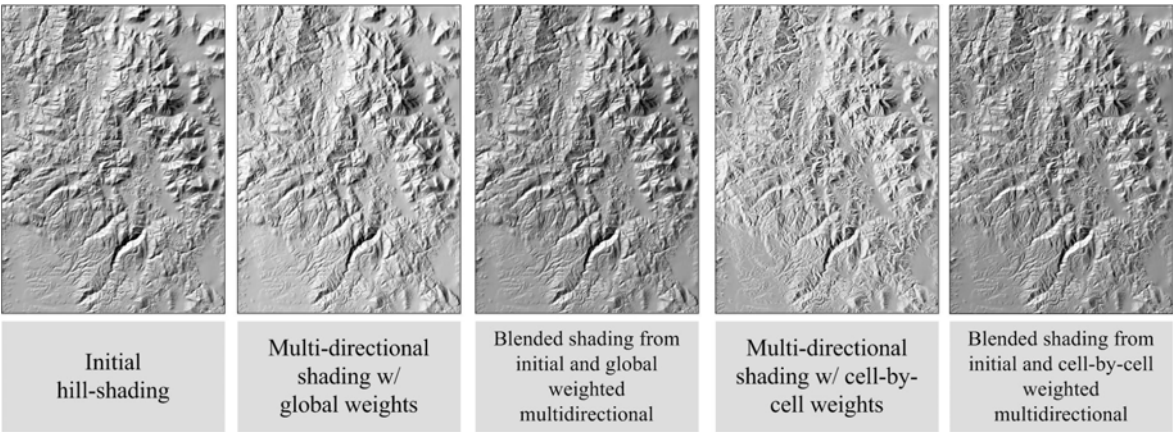
Figure 4. Results for 25-meter test area "Arkadia" (approx. scale 1:900.000)

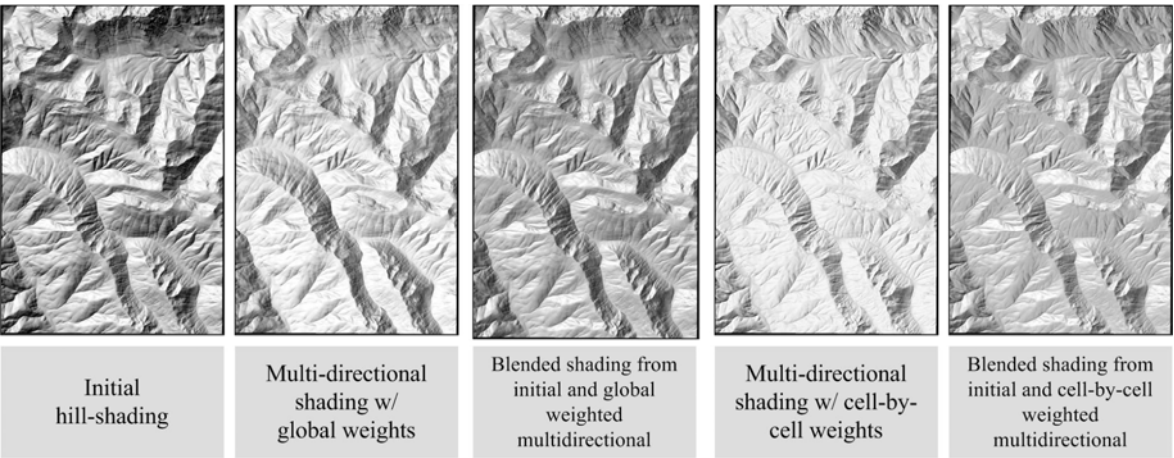| Initial hill-shading | Multi-directional shading w/ global weights | Blended shading from initial and global weighted multidirectional | Multi-directional shading w/ cell-by-cell weights | Blended shading from initial and cell-by-cell weighted multidirectional |

Figure 5. Results for 10-meter test area "Washington", (approx. scale 1:300.000)

4. DISCUSSION

Having the chance to completely automate the process, it is possible to deal with the final form of the models after a sufficient number of tests that make more clear some specific details. For example, the statistical analysis of aspects used in the first model, in order to determine the values of global weights for the components of multi-directional shading, was initially based on the classification of the aspects in four pairs of diametrically opposite ranges. The reason for this suggestion is to better record the main relief forms, but the first percentages of the analysis, made on the small-scale DEM (test area "Arkadia" with 25-meter grid), were uniformly distributed, showing that relief forms have rather spherical than linear shapes. Considering that such types of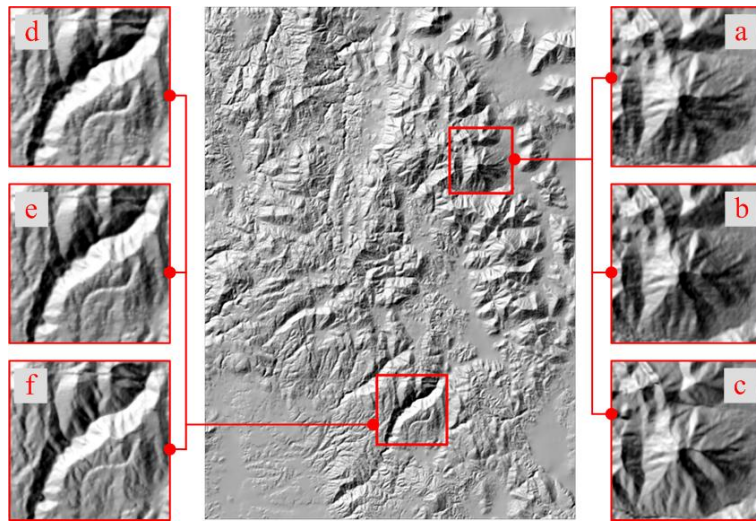 poor relief are expected either in small-scale DEMs or in lower heights' areas, the solution of counting only the cells facing to the four main directions of shading was finally preferred, due to the fact that it can provide more polarised weights even in cases like that. For the same reason, areas with small slope values were excluded to avoid confusion in the estimation of dominant aspects.

Figure 6. Detailed results on 25-meter area "Arkadia"

(a) and (d) initial hill-shading, (b) and (e) blending with global weighted multi-shading, (c) and (f) blending with cell-by-cell weighted multi-shading

In Figure 6, magnifications of two selected local relief forms in test area "Arkadia" are shown, as presented on the initial hill-shading image (a and d), on the image resulted after blending with global weighted multi-shading (b and e) and on the image resulted after blending with cell-by-cell weighted shading (f and c). In both examples, one can notice that the model based on blending between the initial hill-shading and cell-by-cell weighted multi-shading has much better results, allowing details of the forms in dark areas that were previously stayed unseen, to be revealed. The model based on global weighted multi-shading has here a rather slight and sometimes imperceptible impact.

In Figure 7, similar samples are shown from two selected local windows of the test area "Washington" and labelled with letters from (a) to (f) in the same way like in Figure

6. Due to the higher resolution of DEM, the results are much more impressive. The influence of the first model, based on the blending between the initial hill-shading and the global weighted multi-shading, is pretty distinctive but obvious, while the second model, based on cell-by-cell multi-shading, sharpens and accentuates the details of the areas that were stayed in
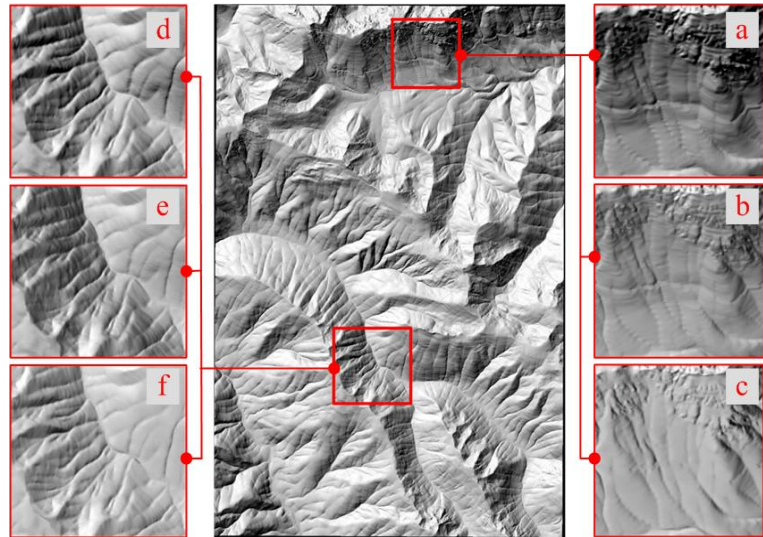

Figure 7. Detailed results on 10-meter area "Washington"

(a) and (d) initial hill-shading, (b) and (e) blending with global weighted multi-shading, (c) and (f) blending with cell-by-cell weighted multi-shading

dark. Nevertheless, by looking at the second example presented in Figure 7 with samples (d), (e) and (f), it must be noticed that in some cases the amplification of light is too much and this causes the reduction of contrast needed in order to separate the opposite sides of a relief form, which is very important for an accurate relief perception.

5. CONCLUDING REMARKS

In this paper an attempt is made to create an analytical hill-shaded image in order to eliminate, at a certain degree, two deficiencies raised from insufficient representation of relief formations, and the presence of deep dark shading tones, which make difficult either to detect the slight relief changes, or even to legibly read the superimposed cartographic symbols. On a technical basis, the models carried out for the experiments of the present study, give the opportunity to fine tune all the stages of computations dynamically and the ability to experiment with different parameters directly, in order to achieve the best possible results. The use of an uniform model containing all the necessary tasks for the production of the final hill-shaded image, is a functional solution providing the frame for gaining time and effort, while preserving a robust environment for the accomplishment of the demarcated goals.

The resolution of the DEM, which is straightforward related to the scale of the collected height data used for the interpolation, is a very important factor for the quality and level of detail found in digital shaded relief. The results confirmed the indication that

the most sufficient is the resolution and quality of the input DEM, the more clear and impressive are the effects from the models on terrain portrayal of the final output hill-shaded image. The use of global weights for multi-directional shading based on statistics of aspect (first model) has a rather slight impact on the final output, as expected. The distribution of weights is applicable to the corresponding hill-shaded images as a whole. On the contrary the use of the model based on blending between the initial hill-shading and cell-by-cell weighted multi-shading (second model), has much better results as are applicable in every structural element of the relief. However, someone should pay attention in some cases, where amplification of light is too much and this causes the reduction of contrast needed in order to separate the opposite sides of a relief form, which is very important visual clue in analytical hill-shading. The computation of the incident angle for each pixel in the DEM and the transformation of this value to a weight factor, proved to be a rather satisfactory and functional solution for the integrated procedure, because it was the critical parameter for the merging of the two corresponding raster datasets, in order to form the final enhanced hill-shaded image.

In general, as the creation of an effectively designed hill-shaded image for cartographic use is a rather complex problem, it should involve more than strict devotion to isolated theoretical principles. Furthermore, the traditional algorithms in use for the production of analytical hill-shading appear to be mainly oriented in the computation of reflectance ignoring the deficiencies arisen from this approach. Thus, it is up to the cartographer's inventiveness to deal with these problems and blend the best traits of the principles, in analytical relief shading, in order to achieve better results. The methodology presented in this paper combines effectively different lighting directions in order to produce significantly improved outcomes compared with single lighted hill-shaded images.

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