Sine Wave, Clustering and Watershed Analysis to Implement Adaptive Illumination and Generalisation in Shaded Relief Representations

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Abstract. Searching for a standardised way to replicate the Swiss style of relief shading, we developed several methods, such as sine wave and others including clustering and watershed analysis, and applied them to the shaded relief representation. The main technique is built on a sine wave equation and was developed to automatically change the light direction based on aspect. To allow terrain generalisation, we implemented two additional methods deploying clustering aspect and watershed analysis. Clustering is fully automated, though it requires some tuning to eliminate noise and to smooth the clustered areas. On the contrary, watershed analysis is not automated and depends on the user experience, but allows us to extract areas between ridges and drainage precisely. Finally, changes of tone implemented in the aerial perspective toolbox help to increase the contrast differences between valleys and ridges and as a consequence to highlight all the most important geomorphological shapes. These tools increase visual quality of shaded relief, standardise the process of producing hillshading and enable consistency of results.

Keywords: shaded relief, sine wave, clustering, watershed, multiple light sources, aerial perspective

1. Introduction

Relief shading is a technique to depict topography on maps in a way that it is intuitively understood by the user (Jenny & Räber 2002). Due to the importance of relief depiction on maps, relief shading is considered to be the framework for the rest of the elements of a map (Imhof 1965).

For many years cartographers tried to produce shaded relief using diverse techniques. Fridolin Becker, being a prominent representative of the Swiss school of cartography, summarised a variety of techniques inherent to the Swiss cartography and introduced the so called Swiss style relief shading. These techniques comprise contrast enhancements for the higher elevations, decreasing the contrast towards the valleys, depicting the lowlands with a grey tone to connect different land forms with one another, and applying the aerial perspective effect (Jenny & Räber 2002). The principles listed were later refined by another Swiss cartographer Eduard Imhof (1965). Further on, the term *manual relief shading* will be regarded as Swiss style relief shading.

The first author who attempted to define mathematical rules for the creation of shaded relief representations and applied the Lambert cosine law to topographic surfaces was Wiechel (1878). The only problem was that in the 19th century the only way to produce Lambertian shaded reliefs was to solve the cosine equation for each point in the map. That caused the method to be quickly forgotten, until the 1950s when Yoëli (1959, 1965, 1966) employed newly developed computers to create a framework for the extensive application of the cosine law. The process was still much too slow for today standards and it took Yoëli several attempts to perfect it; but still this was the first successful attempt of creating analytical hillshading representations based on consistent and reproducible mathematical equations. This method is still in use today and in most GIS applications it remains unchanged. The development of the Digital Elevation Model (DEM) derivatives (Evans 1979) has, however, highly decreased the workload required to produce shaded relief, and today this process is a matter of seconds. As the analytical approach takes distinctively less time and resources, and is also more objective than manual relief shading, it is needed to be automated. At the same time, it suffers in legibility, aesthetic quality and unnecessary greater level of detail (Jenny & Räber 2002). Existing methods cannot replace manual relief shading; they need to be improved first. As long as there is no real alternative to replace manual relief shading, it inalterably serves as a pattern to compare to. Therefore, computers should not only be used to speed up the production process, but also to simulate manual relief shading as precisely as possible. As a consequence, there is a need for a tool that would automate the process and bring consistent results and in the same time would let the user customise analytical relief shading in a way manual shading does.

For this reason we worked on creating GIS tools to increase the visual quality of shaded relief representations. The major development of the project was the creation of a method, based on a sine wave equation to continuously change the orientation of the light vector. Moreover, we also explored two techniques (aspect clustering and watershed analysis) that include forms of terrain generalisation, so that only the most important landforms are highlighted and distracting details are excluded from the shaded relief. Finally, we implemented changes of tones to further increase contrast at higher altitudes and remove details in the valleys corresponding to the Swiss Style of relief shading.

2. Material and Methods

2.1. Study area

The test area of approximately 440 km² is located in the Lepontine Alps on the south of Switzerland (*Figure 1*). The main reason for choosing this specific area was that it is topographically heterogeneous, having both wide and narrow valleys and peaks of different orientation relative to the light source. Accordingly, it should be sufficient to try the method on this area only, as it gives a diverse sample of landforms.

Figure 1. Location of the study area.

One feature that made this particular region challenging for trying the enhancement of analytical relief shading was that one of the peaks, Pizzo Erra (2416 m, *Figure 2*), stretches from the Northwest to the Southeast, i.e., parallel to the Northwest light direction (generally recognised as a standard light direction). Such orientation usually results in a very similar grey tone on both sunlit and shadowed sides of the ridge. As a consequence, its elevation visually seems lower compared to neighbouring peaks, whereas in reality they all are approximately of the same height. Adjustments of sharpness to implement within the area are aimed at contrast enhancements at the shadowed slopes, especially those oriented in parallel to the light direction, to differentiate the two slopes and enhance visual appearance of relief on the whole.

The large valleys Leventina and Blenio spanning across the city of Biasca and to the North of the area also draw attention to its depiction in analytical shaded relief. Traces of human activity present on high resolution DEM not only distract attention but may also cause obstacles when it comes to watersheds extraction.

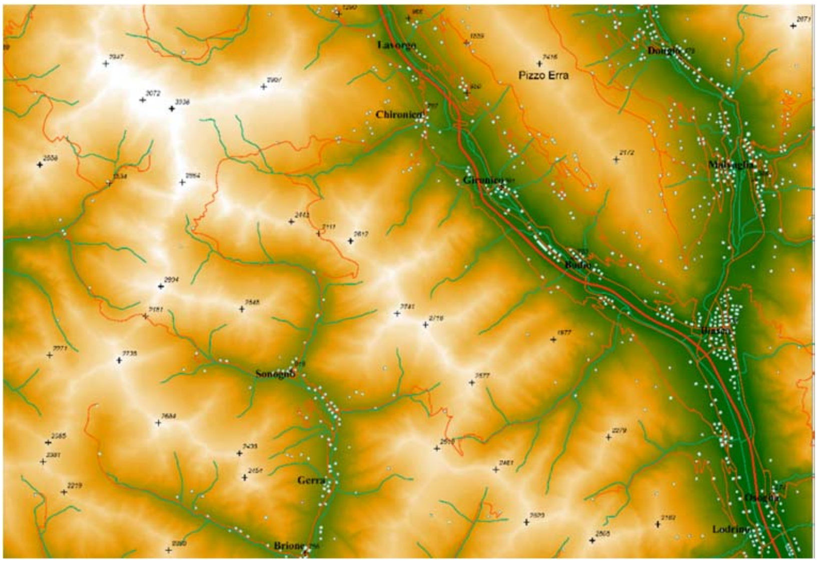

Figure 2. General map of the study area.

The DEM is depicted here with a colour profile that stretches from green values for low altitudes (the main valley in the East has altitude varying from 250 to 400 m), to brown and white for mountain peaks, for which we provide the absolute altitude. The main drainage network, roads and cities are also depicted and taken from the Vector200 dataset (swisstopo, 2014).

2.2. Changing the light direction automatically using a sine wave equation

In this method we experimented with ways of changing the light direction dynamically throughout the scene without any particular constrain.

We started our investigation by analysing the standard hillshading algorithm, where the grey tone of each cell of the DEM is computed as follows:

$$\text{Shading}=255\times(\cos(Z)\cdot\cos(Sl))+(\sin(Z)\cdot\sin(Sl)\cdot\cos(Az-As)), \quad (1)$$

where *Sl* is slope, which is the angle between the tangent and horizontal planes at the given point of the topographic surface, *As* is aspect, a clockwise angle between the North and a projection of the vector normal to the horizontal plane (Florinsky 2012), *Az* is azimuth, the direction of the light vector, and *Z* is zenith, which is the inclination angle above the horizon of the light vector. All these values are expressed in radians. This equation is used in ArcGIS (Esri 2011a) for producing analytical hillshading maps.

In this equation users can modify just two values, namely zenith and azimuth. Slope and aspect are fixed for each cell of the raster and depend on the DEM. In the standard implementation of this method, the user can select a value for zenith and a value for the azimuth and that is the only customisation which can be done. However, if we could find a way to change these two values according to the position of the raster cell in the landscape, we could have a chance of increasing the visual quality of the shaded relief representation, without affecting its objectivity and its level of automation. For doing so we developed a method based on the following sine wave equation to change the light source direction continuously across the landscape:

$$Az=A\cdot\sin(\omega x+\varphi)+\Delta, \quad (2)$$

where *Az* is the azimuth value; *A* is the amplitude of the wave; ω is the frequency of the wave; *x* is the aspect value in degrees, and it is equal to

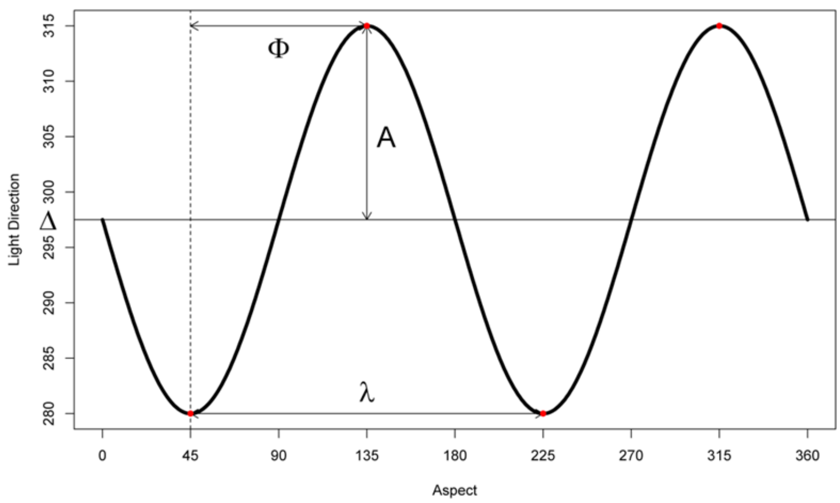

Figure 3. Sine wave. Graphical explanation of the equation's parameters.

$(2\cdot\pi)/\lambda$; φ is the horizontal offset; and finally Δ is the vertical offset.

A graphical explanation of the significance of all these parameters is presented in *Figure 3*. This method can be simply implemented by replacing the *Az* from *Equation 2*11 in *Equation 1*. With this approach the user no longer has to select one single light source, but he can select two light directions, and the equation will implement the two light beams seamlessly in the scene. As it is shown in *Figure 4*, the user can select, for instance, one light source illuminating the scene from 315° and another one illuminating the scene from 280°. In order to calculate the azimuth for each value of aspect of all the cells in the raster, we simply solve *Equation 2*. Basically we are constraining the azimuth to be 315° for aspect equal to 135° and 315°, so for cells perpendicular to the light source. The same is true for the second light source, which takes an azimuth equal to 280° only for aspects of 45° and 225°. For all the other values of aspect the azimuth is allowed to vary smoothly between the two extremes.

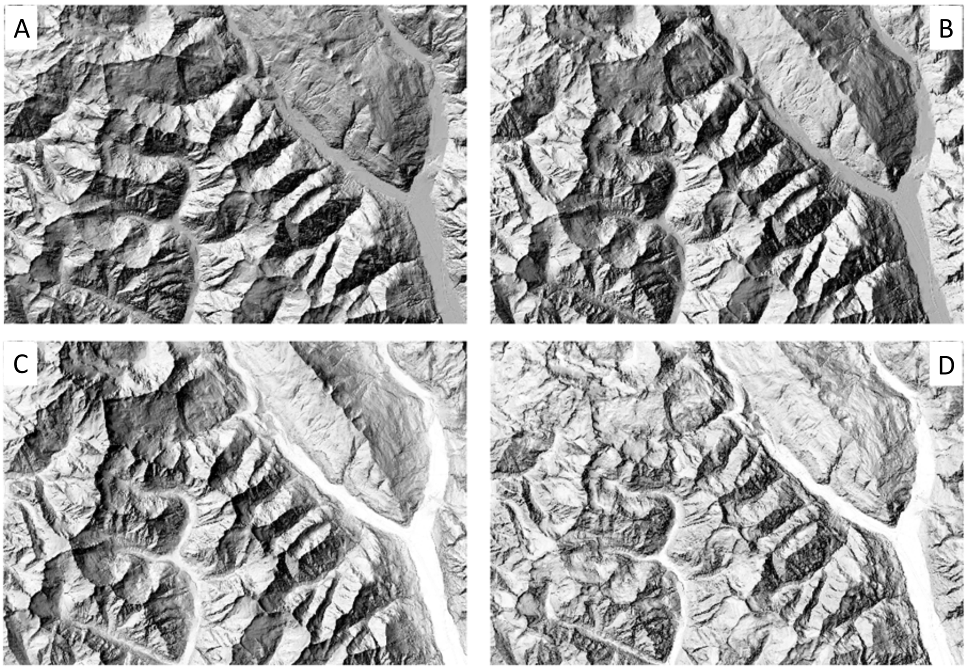

Figure 4. Graphical comparison between:
A) the standard hillshading from ArcGIS (Esri 2011a)
and hillshading with two light sources illuminating from 315° and 280° and a zenith
B) fixed at 45°, C) adjusted according to elevation, D) adjusted according to slope.

We also included two zenith corrections to further highlight details at higher elevations, which are the focus of shaded relief in mountainous regions. In manual shading, valleys are represented with a flat grey tone. A similar effect can be achieved using a light source perpendicular to the ground. On the other hand, if the whole image is illuminated perpendicularly, the tone will be set according to the principle “the steeper, the darker”, the scene would look flat and the only feature that is going to be highlighted is slope. For this reason we created two corrections for zenith, the first according to elevation and the second according to slope, so that the user may decide which features to be highlighted through shading. With these corrections the tridimensionality effect is still present, but practitioners can better customise the final output.

2.3. Changing the light azimuth in shaded relief representation by clustering aspect

In this experiment we tested a way to focus the light changes provided by the sine wave equation to homogeneous geomorphological units. Terrain segmentation is a key part of shaded relief, since it allows the cartographer to better highlight the most important landforms in the landscape, while removing distracting details. In this test we used clustering to extract homogeneous geomorphological units based on their aspect value.

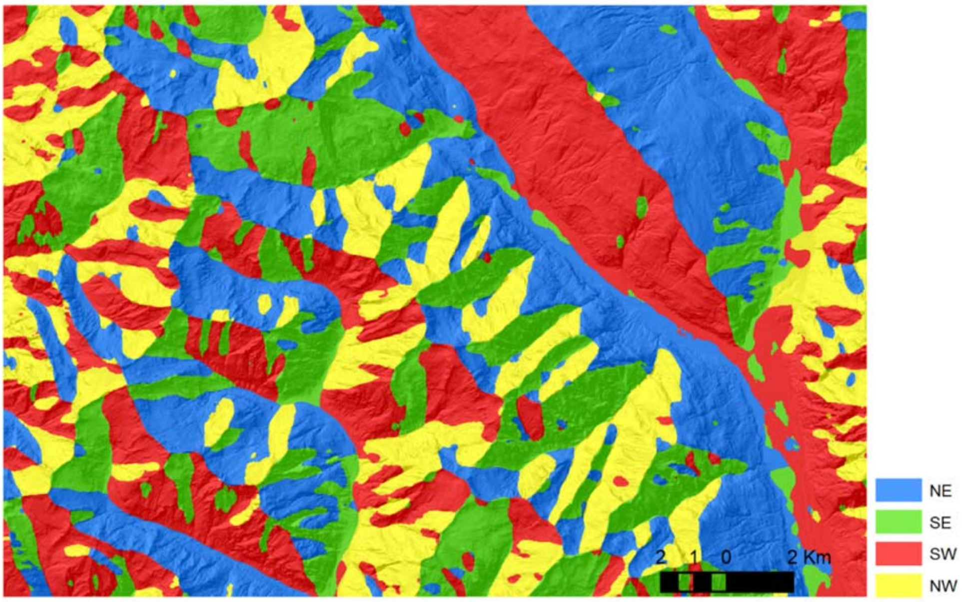

Figure 5. Example of clustering used to segment geomorphological units.

Clustering is a statistical technique that allows the subdivision of a dataset into homogeneous subsets. In this research, clustering is employed to divide the aspect derivative of the DEM that gives the direction each cell of the DEM is facing towards. Subdividing aspect into four main directions (0-90°, 90-180°, 180-270° and 270-360°) should enable the extraction of major landforms (*Figure 5*). This in fact should guarantee that ridges and channels will have one side belonging to one cluster and the other belonging to another cluster. A problem with this technique lies in the level of details of clustering. If a cluster analysis is performed using values of aspect calculated using a 3x3 cells window, the result is going to be too detailed to be useful for shading. The only way of obtaining meaningful clusters is to smooth the results until the clusters' outer boundaries are close to the ridge lines.

Once the clusters, identifying regions that should be illuminated by the same light source, are obtained, we again implemented a modification of *Equation 2* to automatically change the light beam according to the cluster division.

As this method divides the landscape into homogeneous geomorphological units and then illuminates each with the same light beam, for some areas it provides better results than the sine wave used alone. The problem, however, is that the terrain is too complex for the clustering to correctly identify all the ridges. The smoothing partially solves this but the shaded output still does not provide the level of crispness in the ridges typical for the Swiss Style relief shading.

The detailed description of the method based on a sine wave (Veronesi & Hurni 2015), clustering method (Veronesi & Hurni, 2014) and the ArcGIS tools[i] designed are publicly available.

2.4. Watershed shading

Based on the conclusions of the previous experiment, we realised that landscape segmentation is a crucial part of the process of relief shading. However, clustering does not produce perfect results, even though it is fully automatic. For this reason in this final research we tested the use of watershed analysis. Watersheds are appropriate elements for shaded relief, since they enable the correct separation of each area along ridges.

A watershed, or a drainage basin, is the area from which a channel, stream, or river draw its water. All the falling snow and rain in a single watershed are collected into a single channel. Watershed analysis began in the 1950s and 1960s with the creation of digital computers. The first algorithm developed for this purpose was the Stanford Watershed Model, which included functions and tools that are still in use today (Donigian 2006). In this work, the watershed analysis was performed with ArcHydro module (Esri 2011b), which is an ArcGIS based tool for hydrological analysis. It allows the user to extract the geomorphological divides for each drainage basin starting from a digital elevation model (DEM).

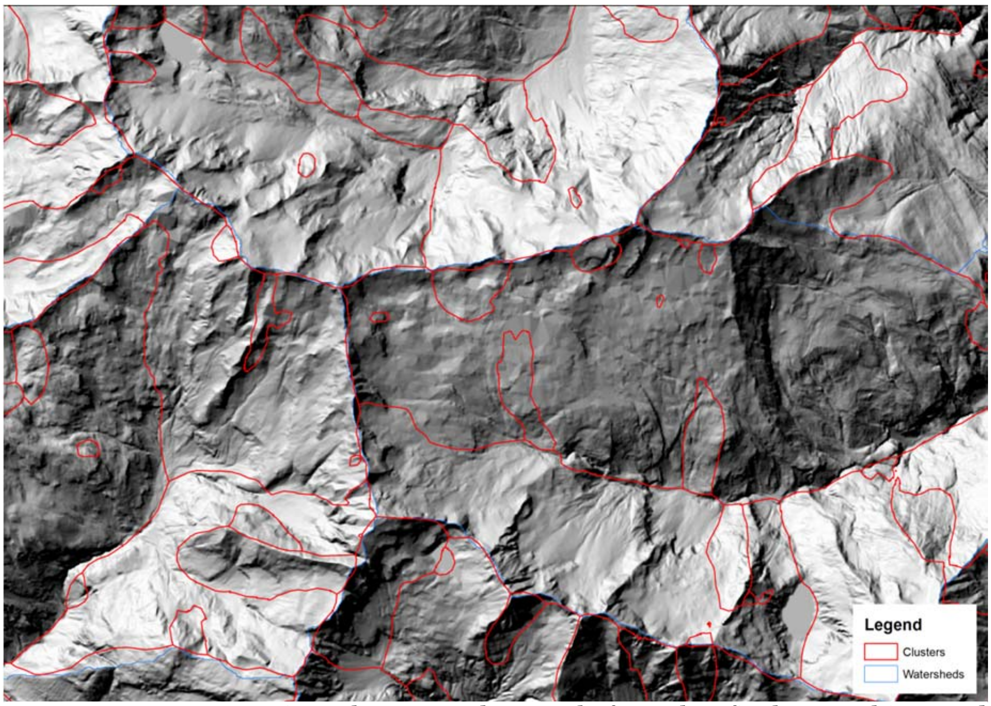

Figure 6. A comparison between clusters before the final smoothing and watersheds.

Figure 6 shows a comparison between clusters before the final smoothing and watersheds. It is clear in this image that watersheds are perfectly able to delineate all the ridges with very good accuracy, while clusters create lots of artefacts. As mentioned, in this image clusters are depicted before the final smoothing phase, which allows some of these artefacts to disappear, as discussed in Veronesi & Hurni (2014).

We performed the watershed analysis at various scales, by adjusting the minimum length of drainage that is considered to be a part of a separate watershed. The minimum value that can be set in the application is 1 km, and this extracts very small watersheds. On the other end of the spectrum, we defined a maximum length of the drainage of 150 Km, which extracts watershed bounded only by the most prominent ridges. The choice of the most suitable dimension of watershed depends on the scope of the shading and the scale of the final output. In this study, as we are dealing with a DEM with 10 m of pixel size, we opted for 100 km of drainage length, which guarantees large enough watersheds that segment only the important ridges in the area.

We developed several tools[ii] in ArcGIS to provide illumination to the scene, using the sine wave method, plus a novel way to increase the visual quality of the output using the atmospheric perspective[iii]. This is a visual trick that manual cartographers used to employ in order to increase the sharpness of the ridges and smooth valley.

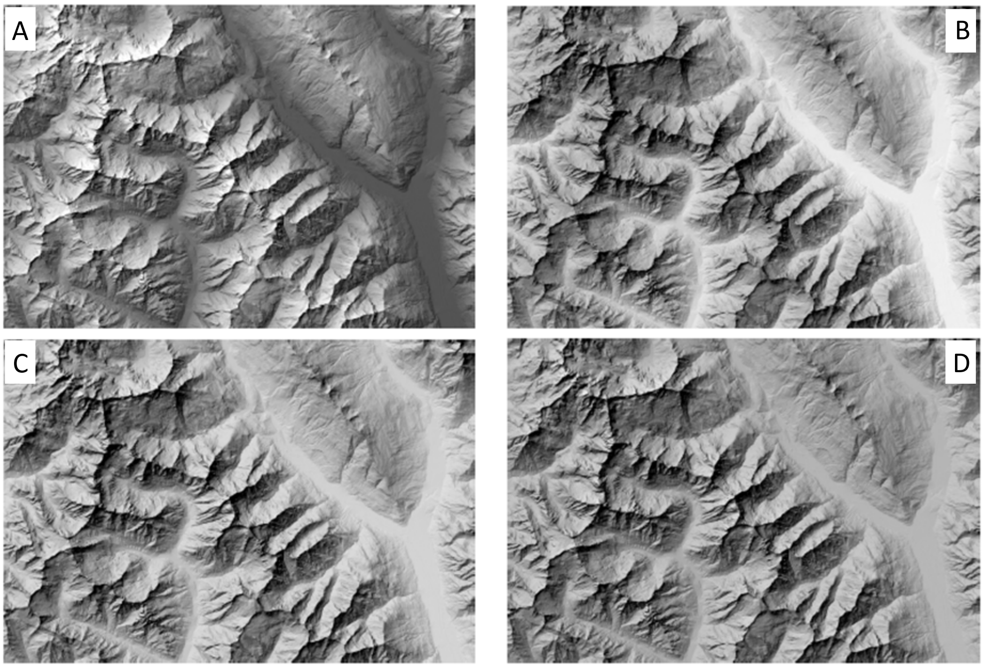

Figure 7. Aerial perspective effect calculated with a user-definable parameter equal to A) 1 (maximum obscuring), B) -1 (maximum clearing), C) -0.5 and D) -0.3.

As a first step, two existing approaches for calculating the aerial perspective (Brassel 1974, Jenny 2001) were implemented as ArcGIS Geoprocessing models using ArcGIS built-in functions, ModelBuilder and Python programming language. They resulted in the following effects: emphasizing sharpness of ridges and placing the haze effect in the lower elevations. At this step the user by choosing parameters can determine a degree of brightness (clearing) or darkening (obscuring) of the output image, which is demonstrated by Brassel's method in *Figure 7*.

Second, DEM and the shaded relief were cut by watershed boundaries and the aerial perspective was applied locally within an area of a watershed (*Figure 8B*).

As a positive consequence of applying aerial perspective effect, noise is reduced leading to less visual distraction in the valleys. At the same time the ridges oriented parallel to the light direction are still indistinct; this can

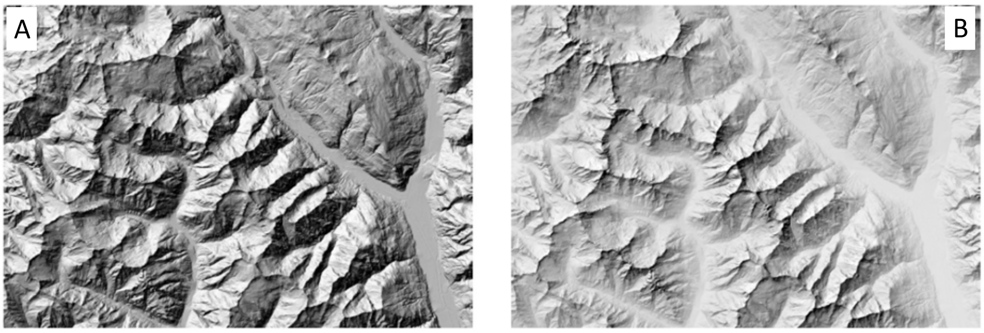

Figure 8. A comparison between A) default shaded relief generated using ArcGIS Hillshade function (Esri 2011a) and B) the same shaded relief with the aerial perspective effect applied locally within watersheds using the designed tool based on Brassel (1974).

be solved as a next step by changes of light direction within watersheds. Thus, the shaded relief with the aerial perspective effect applied to watersheds was complemented with the light changes within watersheds and the two light sources illuminating the terrain from the Northwest and West to accentuate ridges stretched parallel to the standard light direction (*Figure 9*).

Though the method requires some user-definable parameters and may be complemented by the consequent changes of light direction, this is a step closer to a fully-automated method to create the aerial perspective effect. Besides, this approach is quantitative, consistent, reliable, and more objective than older techniques.

Figure 9. Shaded relief generated using the ArcGIS Hillshade function combined with the aerial perspective effect calculated within watersheds, complemented with light changes within watersheds and the two light sources originating from the Northwest (315°) and West (280°).

3. Conclusion

For decades manual relief shading was the only solution to provide landscape representations that can be intuitively understood even by non-cartographers. The advent of fast computers provided the opportunity to translate the concepts of manual shading into algorithms capable of producing comparable landscape depictions. As a result, algorithm of the hillshading was created, which is nowadays present in almost every GIS application. This algorithm is completely automatic, therefore fast, reliable and is able to produce consistent results. It is a great advantage compared to manual shading in which a certain level of subjectivity is always involved, meaning that the results are highly variable.

The flipside of analytical hillshading, as it is currently implemented, is that it does not include all the changes and details that made manual shading so popular. For example, it allows only one light source and does not implement any zenith correction, thus decreasing the visual quality of the shaded output. In our research we tested methods to increase the visual quality of shaded relief, while maintaining similar levels of automation and consistency, typical for analytical hillshading.

The major development of the project was the creation of a method, based on a sine wave equation, to continuously and automatically change the orientation of the light vector. This method was originally developed to work independently by changing the light direction based only on aspect. By solving the sine wave equation using aspect, we are able to seamlessly change the light direction between two light sources, thus producing a much more informative shaded relief. Since this method is purely based on aspect and a mathematical equation, it can be applied with consistency, and being available as an ArcGIS toolbox, it is also extremely easy to use even by non-cartographers.

This method, however, does not support any form of terrain segmentation, which is very useful. On the one hand, it allows a cartographer to hide distracting details. On the other hand, it provides a way to highlight important geomorphologic features. To overcome this limitation, we implemented two additional methods, based on clustering aspect and watershed analysis. As mentioned before, clustering is fully automatic but requires some tuning to eliminate noise and smooth the clustered areas. Only after these corrections we can obtain clustered areas that are geomorphologically meaningful. However, even then not all the relevant areas are properly covered, in some cases smoothed clusters do not properly follow ridge lines, and this causes some artefacts. On the contrary, watershed analysis allows us to precisely extract areas between ridges and drainage, which is the general focus of shaded relief. However, the process is not automatic, it requires user intervention and its results depend on the user experience and the accuracy of the algorithm.

Finally, the use of multiple light sources is not the only visual device used in manual shading. Changes of tone are also widespread to increase the contrast differences between valley and ridges and as a consequence highlight all the most important geomorphological shapes. To automate this aspect we developed three possible solutions. The first two methods transform elevation or slope into weights and then modify the light vector inclination based on them. This allows us to set the inclination of the light vector to 90° for low elevation (i.e., valley) in order to obtain a constant whitish tone that masks urban areas and the noise in the DTM along highly populated valley. The inclination then decreases with elevation up to a minimum value, which can be set by the user, to gradually increase the image tone along slopes. The final approach we developed was the translation of two existing methods to calculate aerial perspective effect into ArcGIS and its subsequent application within watersheds. The models designed in ArcGIS allow us to simulate both tonal changes and the aerial perspective, which are essential parts of the Swiss style of relief shading. The corrections guarantee a blackish tone along sharp and high ridges (on the shadow side) and white on the light side as Imhof suggested.

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