MOUNTAIN AREAS SOLAR RADIATION SPATIAL DISTRIBUTION ANALYSIS BY USING WATERSHEDS DIGITAL ELEVATION MODELS

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Abstract: *The paper presents a procedure for establishing some peculiarities of the solar radiation in mountain regions, using the digital elevation models. A set of formulas is given for calculating the direct solar radiation received by various surfaces as a function of the incidence angle. Using the thematic maps with the slope gradient and aspect of each raster cell, the layers with the equivalent latitudes and longitudes were calculated for the experimental watershed Valea Băii. The differences between the various areas within the watershed are illustrated by the area distribution on classes of equivalent coordinates. These variations are affecting the local climate and should be considered for climate change scenarios at tree stand level.*

Key words: *solar radiation, digital elevation models, equivalent latitude.*

1. Introduction

The natural systems and their specific processes show an obvious spatial variability and certainly a time variation. Their complexity imposes the system mathematical modeling and process simulation as major research methods and useful tools in the decision making process concerning the natural resources management. We consider that their importance will increase in the future, in the context of human induced environment modifications, such as the largely debated climate changes, which will make inappropriate many management "golden rules" derived from past experience.

The mountain watersheds are characterized by large data sets referring to geology, land forms, climatic conditions, soils, vegetation and certainly to the different land uses and their management scenarios. The complex watershed model (realized in an analytical raster GIS) is definitely a mathematical model, but it differs from the classical ones by using functions synthetically defined through tables of values instead of analytical functions. These synthetical functions, f(x,y), are the arrays, the layers of the GIS raster representation. The GIS modules enabling cartographic and especially 3D-views lead to some similarities with the physical models, creating genuine computer "virtual laboratories".

The watershed models, comprise a large number of layers, thematic maps, referring to morphometry, cover etc. The core of these models is represented by the digital elevation model (DEM), an array (matrix) with cell elevation values. In this way, the landforms could be accurately represented

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at “meso” (medium) level, but certainly, the geomorphologic details (at micro scale) are stochastically distributed. The accurate representation of the geomorphology makes a great difference, because the landforms are the backbone of the site, enabling us to take account of: the different microclimatic conditions (dependent on steepness, aspect, slope position - and also influenced by soil and cover peculiarities), soil properties spatial variation (its depth, clay content etc. are obviously varying along a hill-slope), etc. These digital models are useful for simulating a wide range of natural processes, because a watershed represents a geo-system, a complex system integrating several related ecosystems, therefore a basic unit for many geophysical and biological processes. Thus, the watershed models are useful for applications in mountain climatology, in forest soils and site analysis, generally in mountain and forest ecology.

2. Solar Radiation Calculations

Solar radiation incidents outside the earth’s atmosphere are called extraterrestrial radiations [4]. On average the extra-terrestrial radiance, also called the ‘solar constant’, is 1367 W/m^2, but this value slightly varies during the year. The extraterrestrial radiation for each Julian day (n, counted from January 1st) could be calculated, using the following formulas:

$$I_0 = 1367 \cdot [1 + 0.034\cos(\beta) + 0.001\sin(\beta) + 0.0007\cos(2\beta) + 0.0001\sin(2\beta)]\ [\text{W/m}^2], \quad (1)$$

$$\beta = 2\pi n / 365\ [\text{radians}]. \quad (2)$$

The higher values of the ‘solar constant’ are recorded in the boreal winter, around January 4th, when the Earth is closest to the Sun and the lower one on July 5th, when it is furthest.

As it passes the atmosphere, the solar radiation suffers extinction, through absorption and scattering, which depends on the transparency coefficient (reverse of the extinction coefficient), and the optical depth (or air mass). Consequently, the intensity of radiation on a surface perpendicular to the beam could be calculated using the equation expressing the Beers-Bouguer Law:

$$I = I_0 \cdot p^{\frac{1}{\cos(z)}}, \quad (3)$$

where:

I - radiation intensity on normal surface (perpendicular to the beam) [W/m^2];

I_0 - solar ‘constant’, [W/m^2];

p - total transparency coefficient [−];

z - the zenith angle (the angle between the sun beam and the vertical line).

The zenith angle (z), which is complementary to the solar “height” angle (h_0 = 90^0 − z), could be calculated using the following trigonometric relation:

$$\cos(z) = \sin(\lambda)\sin(\delta) + \cos(\lambda)\cos(\delta)\cos(\omega), \quad (4)$$

where: λ - the latitude of the location; δ - the declination of the sun; ω - the hour angle.

The declination of the sun is the angle between the earth’s axis and the plane perpendicular to the line between the earth and the sun. An approximate formula for the declination of the sun is given below:

$$\delta = 23.45 \cdot \frac{\pi}{180} \cdot \sin\frac{2\pi \cdot (284 + n)}{365}. \quad (5)$$

The hour angle could be calculated for any moment, usually for any hour, after computing the solar time (T_{solar}):

$$\omega = \frac{\pi(12 - T_{solar})}{12}. \qquad (6)$$

By multiplying the radiation intensity, I [W/m^2], on the normal surface, given by (3), with cos(θ), where θ is the angle between the vertical and the perpendicular to the considered surface, one can obtain the values corresponding to an elementary surface having the inclination α and being rotated γ degrees from the south-north direction.

3. Equivalent Latitude and Longitude Determination for an Experimental Watershed

In order to test the possibilities offered by the Geographical Information Systems for establishing the spatial distribution of the direct solar radiation in a mountain area we considered an experimental watershed, Valea Băii, located south of Braşov, in the Piatra Mare Mountains for which the digital complex model [2], as described in the introduction, was realized.

Using the digital elevation model and the context operators, the layers with the slope inclination and aspect for each cell were produced and these are illustrated in Figure 1.

For calculating the incoming radiation on a surface that is not horizontal, we can consider that its inclination (α - slope gradient) and the azimuth angle (γ - aspect), determine a latitude and longitude modification. These equivalent latitude (*eqlat*) and longitude (*eqlong*) could be calculated using the relations (7) and (8) given below [1], [3].

By substituting the latitude and the longitude in formula (4), and operating several simplifications we come to the equation (9), which can be used for establishing the angle θ, and consequently the incoming solar radiation for any raster cell at a certain moment (the day and hour giving the δ and ω angles).

In equations (7) and (8), using the arrays of slope and aspect values, with the *Image Calculator* module of *Idrisi,* the equivalent latitude and longitude were calculated for each cell. The percentage distribution of watershed area on categories is shown in Figure 2.

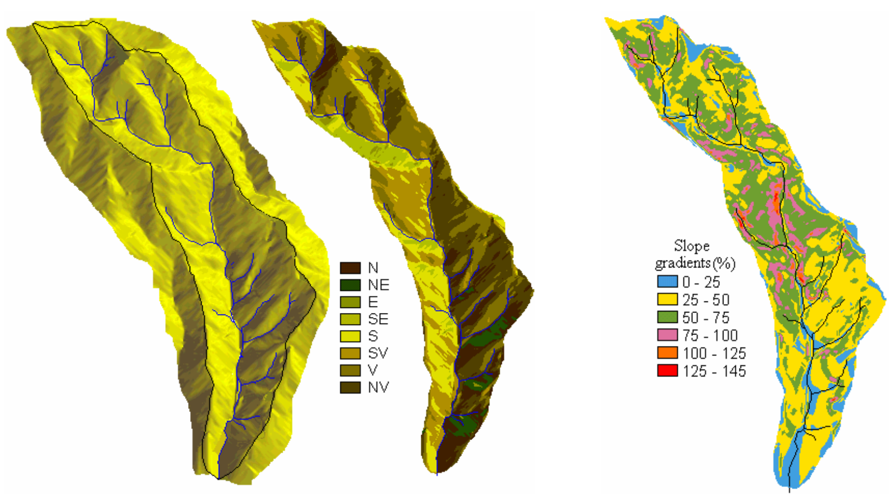
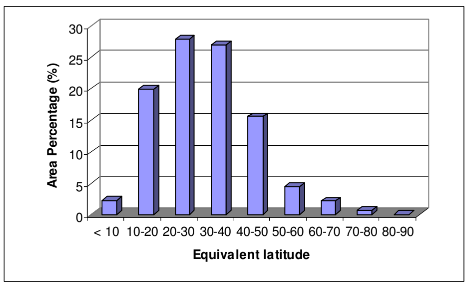


Fig. 1. *Thematic maps of aspect and slope gradients for the Valea Băii watershed*

$$eqlat = \arcsin[\cos(\alpha)\sin(\lambda) + \sin(\alpha)\cos(\lambda)\cos(\gamma)], \quad (7)$$

$$eqlong = \text{arctg}\frac{\sin(\alpha)\sin(\gamma)}{\cos(\alpha)\cos(\lambda) - \sin(\alpha)\sin(\lambda)\cos(\gamma)}, \quad (8)$$

$$\cos(\theta) = \sin(\delta)\sin(\lambda)\cos(\alpha) - \sin(\delta)\cos(\lambda)\sin(\alpha)\cos(\gamma) + \cos(\delta)\cos(\lambda)\cos(\alpha)\cos(\omega) + \cos(\delta)\sin(\lambda)\sin(\alpha)\cos(\gamma)\cos(\omega) + \cos(\delta)\sin(\alpha)\sin(\gamma)\sin(\omega). \quad (9)$$



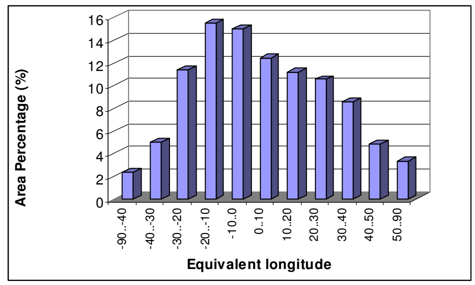


Fig. 2. *The class distribution of equivalent latitude and longitude in Valea Băii watershed*

4. Conclusions

The equivalent latitudes should not be considered as indicating climate conditions comparable to those on the same coordinates on Earth (raster cells with low equivalent latitudes are not in tropical conditions) but offer a sound basis for analysing the differences between various elementary areas. On the hill-slopes, the solar beams are heating the land more than on similar horizontal surfaces. In Figure 2 we can observe that almost all the watershed is characterised by equivalent latitudes lower than the real geographic one (45^o).

The equivalent longitudes are indicating the “time change” in the solar radiation daily regime, respectively the moment of maximum incoming energy. From Figure 2 it results that the equivalent longitudes are more evenly distributed within the catchment. Anyway, there are more cells with positive corrections due to the general orientation of the watershed.

These parameters are useful for comparing the meteorological data measured at cell level and determining the spatial variation pattern. On this basis it is possible to evaluate the impact of the possible climate changes at local level.

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