HIGH RESOLUTION GRID OF POTENTIAL INCOMING SOLAR RADIATION FOR SERBIA

by

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Original scientific paper
DOI:10.2298/TSCI150430134L

Solar radiation is a key driving force for many natural processes. At the Earth's surface solar radiation is the result of complex interactions between the atmosphere and Earth's surface. Our study highlights the development and evaluation of a data base of potential solar radiation that is based on a digital elevation model with a resolution of 90 m over Serbia. The main aim of this paper is to map solar radiation in Serbia using digital elevation model. This is so far the finest resolution being applied and presented using this model. The final results of the potential direct, diffuse and total solar radiation as well as duration of insolation databases of Serbia are portrayed as thematic maps that can be communicated and shared easily through the cartographic web map-based service.

Key words: *solar radiation, digital elevation model, web-maps, Serbia*

Introduction

Solar radiation is a major driving force of the physical, biological, hydrological, and agricultural processes [1]. The study of solar radiation is particularly important recently in the context of climate change [2]. A global decrease in solar radiation of -0.51 ± 0.05 W/m^2 per year has been recorded between the period of 1950 and 1980, which is 2.7% per decade [3]. This decreasing phenomenon is known as global dimming [4]. In contrast, the opposite trend has been noted since 1980, and is known as global brightening, which is characterized by an increase in overall solar radiation [5].

It has been documented that anthropogenic activities have increased atmospheric aerosol concentrations [2] that might be the reason for solar radiation decrease [6]. On the other hand, Streets *et al.* [7] pointed that a decrease in anthropogenic aerosol emissions during the last several decades contributed to an increase in solar radiation. By implying a certain degree of uncertainty in previous findings, Alpert *et al.* [8] highlighted the importance of anthropogenic aerosols in relation to solar radiation on the local and regional level.

The analysis of the spatial pattern of solar radiation and/or insolation is also of great significance [9-14]. Spatial variability of solar radiation can be a key tool in environmental and

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economic planning, and renewable energy strategies. Spatial heterogeneity of incoming solar radiation is determined by many factors besides the atmospheric vapor and clouds, including topography, albedo, and forest canopy [15, 16]. Topography and specifically elevation, slope and aspect are the major factors determining the amount of solar radiation incident on the surface [1]. Different models are used to derive a solar spatial database from both topographic indices and observations [17-20]. Most solar radiation models have been already implemented in the GIS based environmental modeling software packages. The r.sun module [18] of GRASS GIS [21] is the best known open source software based on the methodology that uses equations published in the European Solar Radiation Atlas [22]. One of the first GIS-based solar radiation models was SRAD (solar radiation), which was developed for TAPES_G (Terrain Analysis Programs for the Environmental Sciences – Grid version) [23]. The latest version of this software is available as an ArcGIS module. In this study, we used a module for potential solar radiation within the SAGA GIS environment [24].

Solar radiation model and climatic data are integrated within the Photovoltaic Geographic Information System (PVGIS), which is a European solar radiation database developed period between 2001 and 2005 [25]. The database has a resolution of 1 km × 1 km and consists of monthly and yearly average values of global irradiation and related climatic parameters that cover the period 1981-1990. This database was used by Suri *et al.* [25] to analyze regional and national differences of solar energy resources by assessing the photovoltaic (PV) potential in the 25 European Union member states and 5 candidate countries. The authors designed a web application to provide access to a database that offers the user data on clear sky and real-sky irradiances for a chosen month.

Pons and Ninyerola [26] developed and evaluated a methodology for generating monthly radiation maps for Catalonia based on Digital Elevation Model (DEM) with a resolution of 180 m, field data and GIS tools. They refined the model using several solar radiation observations. The authors suggested that the availability of DEM gives a range of possibilities to scientists dealing with solar radiation.

Apart from meteorological observations and DEM, remote sensing data can also be used in computing solar radiation. Tovar and Baldasano [27] used satellite NOAA data to estimate global solar radiation. This approach is useful considering the sparse coverage of meteorological networks over mountainous areas, particularly the ones measuring solar radiation.

There have been relatively few published studies related to the spatial variability of solar radiation in Serbia [28, 29]. Protic *et al.* [30] have performed 3-D roof modeling for the accurate assessment of solar potential in Serbia for the town of Indjija. The study showed an efficient automated methodology for generating a 3-D model of single-plane and double-plane roofs from Digital Surface Model (DSM) created automatically from stereo-photogrammetry.

The aim of this paper is to map solar radiation in Serbia using DEM of 90 m resolution. This is so far the finest resolution being applied and highlights the novelty in mapping solar radiation using DEM.

Study area

The study area covers Serbia, which comprises around 18% (88,361 km^2) of the Balkan Peninsula. Serbia is characterized by a diverse topography (fig. 1). Its northern parts are entirely located within the Panonian Plain whereas the remainder of the country contains mountainous regions: the Dinaric Alps are located in the western part of the country, the Carpathian and Balkan Mountain stretches along the eastern parts, and the Rhodope Mountains are in the southeast. The altitude varies a great deal from 29 m near the Veliki Timok River and the Danube River confluence (border between Serbia, Romania, and Bulgaria) up to 2656 m on the Prokletije Mountain (in the south). Almost the entire area of Serbia (92%) is drained by the Danube River while the rest of the territory belongs to Adriatic and Aegean drainage basin.

The north of the country has characteristics of typical continental climate with air masses predominantly originating from Northern Europe [31]. On the other hand, the southwestern part of the country is subjected to Mediterranean influences that are modified and suppressed by Dinaric Alps stretching along the coast [32]. Rainfall in Serbia is unevenly distributed. The Northern parts receive below 600 mm, whereas the south up to 1000 mm annually and mountain summits in the southwest receive over 1000 mm per year.

The average annual global solar radiation basis for Serbia varies from 1200 kWh/m^2 per year in the northwest parts up to 1550 kWh/m^2 southeastern areas, while central Serbia receives around 1400 kWh/m^2 annually [33].

Applied methodology and input data set

All recently developed models for calculating solar radiation in the GIS software environment use topographic information contained in a DEM to determine topographic indices such as elevation, surface orientation and shadow casting [16]. However, the implemented algorithms reported in literature are based on different estimation approaches. In addition, application of the same DEM source with different resolutions always produce different estimated values of topographic indices [34], which is especially noted in areas with complex geomorphology. Therefore, these algorithms may provide different values of estimated solar radiation. Finally, the increase in the resolution of the DEM is more computational demanding.

In this study we used SAGA GIS (System for Automated Geoscientific Analyses) open source software, specifically the *Potential Incoming Solar Radiation* module. The detailed description of implemented methodology is given by Bohner and Antonic [19]. They recognized three governing factors that have an effect on the spatial variability of solar radiation: (1) relative orientation of the Earth in relation to the sun, (2) clouds and other atmospheric inhomogeneities, and (3) topography.

The SAGA GIS offers a fairly broad range of input parameters for modeling potential incoming solar radiation; however, we decided to use publically available topographic altitude data (DEM) instead for all derived terrain indices like slope, aspect, sky clear factor, shadow (shading) and geographical coordinates (latitude and longitude). Those input parameters cover the influence of the first and third governing factors on spatial estimation of solar radiation. Whether the impact of the second group of factors will be considered, additional information such as clouds cover should be required.

The direct irradiance is a function of the solar zenith angle, solar flux at the top of the atmosphere, atmospheric transmittance, solar illumination angle on the slope, and sky obstruction. The Zenith angle and solar flux depend on date, whereas atmospheric transmittance is a function of elevation as the number of absorbers decrease with altitude. The solar illumination angle (the angle between a plane orthogonal to sun's rays and terrain) is a function of surface elevation (slope and aspect of terrain) and relative position of the sun in the sky (sun elevation and azimuth).

Daily direct irradiation $S^*_{S(d)}$ could be calculated as [19]:

$$S^*_{S(d)} = \sum_{i=1}^{n} S^*_{S(h)i} = \sum_{i=1}^{n} \zeta_i \frac{S_{S(h)i}}{\sin\theta_i} \cos\gamma_\iota \tag{1}$$

where $S^{*}_{S(h)i}$ represents hourly topographic direct radiation, ζ is the shadow binary mask (0 = shadow, 1 = non-shadow), θ – the elevation angle of the Sun over the horizon, γ – the solar illumination angle, and n is the number of hours used for the calculation of daily radiation sums. In this study for n we used 18 hours (period between 5 a. m. to 11 p. m.).

The diffuse irradiance S_h represents the part of total irradiation received from the sky hemisphere. It is a function of solar geometry, pressure (elevation), and the scattering and absorbing properties of the atmosphere [1]. It is necessary to calculate the sky view factor ψ_s depicting the portion of the sky that may be obstructed by topography for every given location when modeling this partition of solar irradiance [19]:

$$\psi_s = \frac{1}{2\pi}\int_0^{2\pi}[\cos\beta\cos^2\varphi + \sin\beta\cos(\Phi-\alpha)(90-\varphi-\sin\varphi\cos\varphi)]\mathrm{d}f \tag{2}$$

where φ represents the zenith angle to the local horizon for azimuth direction Φ , and β and α represent the slope and aspect of terrain, respectively. The sky view factor ψ_s is a measure that quantifies the ratio of diffuse irradiance at a given point to that on an unobstructed horizontal surface [35]. This parameter varies from 1 (for completely unobstructed terrain surface like horizontal plane landscape or peaks or ridges) to 0 for completely obstructed land surface.

Topographic diffuse solar radiation S^{*}_{h} is given as:

$$S^{*}_{h} = S_h\psi_s \tag{3}$$

The zenith angle φ was also used to calculate the shading of direct irradiance at the point caused by the adjacent terrain. The total radiation presents the sum of topographic direct and diffuse solar radiation. The calculated values are without any atmospheric effects. For that reason it is necessary to reduce calculated data by multiplication with the clearness index K_{T} which is a function of time of year, season and climatic conditions over the particular geographic location [36]. The raster layer of annual monthly averaged insolation clearness index K_{T} over the Serbia (mean value = 0.545; max = 0.605; min = 0.526) with 90 m resolution was made by splines interpolation of data retrieved from this source: https://eosweb.larc.nasa.gov/cgi-bin/sse/subset.cgi

The DEM data

The Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) GDEM global model (Version 1) of Earth's surface, published in the year 2009 (http://asterweb.jpl.nasa.gov/gdem-wist.asp), was used for data on the digital terrain model. The ASTER GDEM data are distributed by the National Aeronautics and Space Administration through its Land Processes Distributed Active Archive Center and is free of charge to worldwide beneficiaries. This database is designed for advanced analyses in disaster monitoring, hydrology, energy, environmental monitoring, *etc*. All data are distributed in GeoTIFF format with a spatial resolution of 30 m and estimated height accuracy of 20 m at 95% confidence, which corresponds to the height accuracy of topographic maps with the scale of 1: 50,000. For the purpose of this study, the initial data were resampled to 90 m resolution. ASTER GDEM version 2 with enhanced ground resolution was recently released in October 2011.

Results and discussion

Considering the fact that topography is presented by a grid of altitude points (DEM), it is clear that height, slope and aspect may vary therefore leading to different shading and reflectance effects [1]. We generated a map of direct insolation (fig. 2) that is predominantly influenced by illumination angle, which includes self-shadowing by the slope itself. This is the reason why northern slopes of mountains in central and southern parts of the country are showing minimum amounts, while southern parts are showing maximum amounts of direct solar radiation (insolation). On the other hand, the diffuse insolation map shown in fig. 3 indicates that irradiance is being obstructed mainly by local topography. Therefore the lowest amounts of radiation are recorded in lowlands on the northern parts of the country as well as along river valleys. In contrast, the highest diffuse radiation is obtained over the Dinaric Alps in the southwest, Carpathian and Balkan mountains on the eastern parts and Rhodopa Mountains in the southeast. Both direct and diffuse insolation are included in the total insolation. The average value for total insolation reduced with clearness index K_T over the whole Serbia (fig. 4) is around 1180 kWh/m^2 (min = 236 kWh/m^2, max = 1652 kWh/m^2) which represents almost the same value in comparison to results obtained from ground stations when cloudy conditions were taken into the consideration.

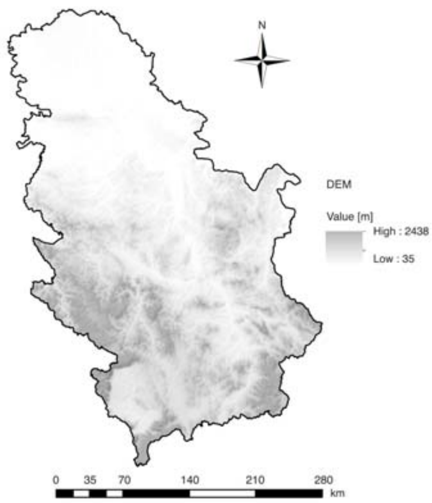

Figure 1. Aster GDEM for Serbia

It is important to add that all maps produced in this study are generated assuming clear sky conditions. Incoming solar radiation is usually expressed through duration of sunshine hours. The generated map of the duration of insolation (fig. 5) shows that the longest duration of sunshine hours are in lowlands of the northern parts of the country (Vojvodina) and including river valleys in central and southern parts of the country (over 4000 hours per year cumulatively). The duration of total insolation decreases with altitude, showing the lowest values on Prokletije Mountain and Sara Mountain.

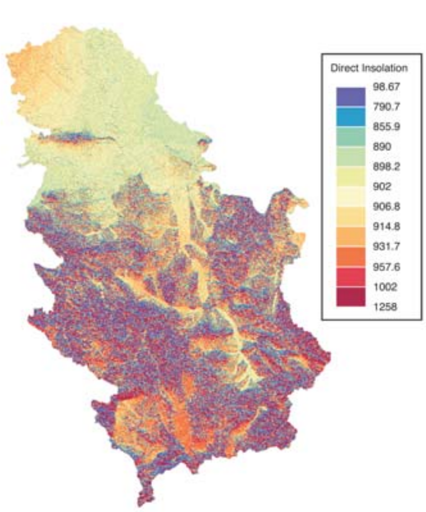

Figure 2. Direct insolation map for Serbia in kWh/m^2

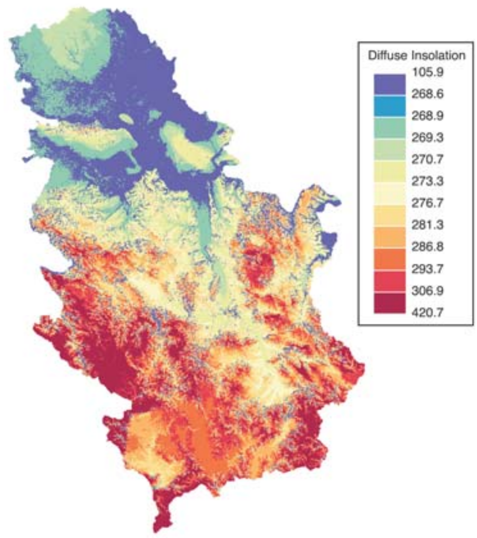

Figure 3. Diffuse insolation map for Serbia in kWh/m^2

Results on spatial patterns of recent insolation duration trends in Serbia calculated using observations (1949-2006) present a slight decrease followed by an increase in the last decades [37]. Similar results are found by Sanchez-Lorenzo *et al.* [38] for the Iberian Peninsula in the period between 1951 and 2004. They found a negative trend at the beginning of the investigated period followed by a recent positive trend.

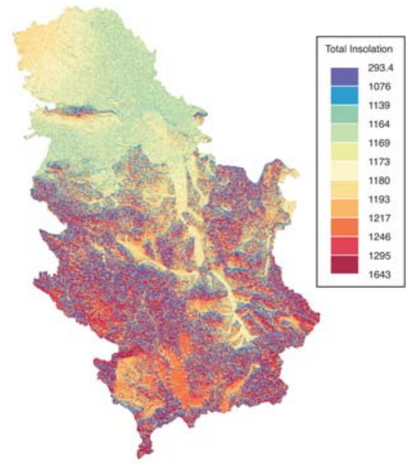

Figure 4. Total insolation map for Serbia in kWh/m^2

Although we did not consider the impact of the DEM's uncertainty on the obtained results, and despite the obvious advantages of using DEM data even over complex terrain [39], it is important to emphasize that the different sources of DEM may produce different outputs for insolation [40].

All of the produced databases are stored in a raster grid format with 90 m resolution and they are georeferenced in UTM (Universal Transversal Mercator) projection.

The final results of the direct, diffuse, and total solar radiation (insolation) as well as duration of insolation databases of Serbia are portrayed as thematic maps that can be communicated and shared easily through the cartographic web map-based service. The web maps were achieved using recently developed packages in the R language environment including the newly developed package plotGoogleMaps [41], which is based on Asynchronous JavaScript and XML technology (AJAX) and Google Maps Application Programming Interface (API) service that produces HTML file map mashups, the product of the combination of geographic data from one source with a map from another source [42]. The web maps are available at URL: http://osgl.grf.bg.ac.rs/materials/insolation.

Moreover, the data of those databases are also available to download for each municipality in GeoTiff format (by clicking on municipality polygon).

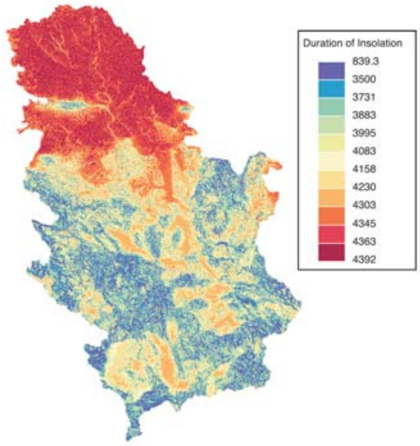

Figure 5. Duration of insolation map for Serbia in hours (h)

Conclusions

In this paper, we depicted the annual data base of potential incoming solar radiation based on a digital elevation model (DEM) with resolution of 90 m over Serbia. The study produced maps showing direct, diffuse and total radiation, as well as duration of insolation that are now offered through web map based services. This is so far the finest resolution being applied and presented using DEM and highlights the novelty of estimating solar incoming radiation using DEM and incorporated GIS tools.

Interactions that happen between atmosphere and topography are very complex. When estimating the actual solar radiation using DEM over a certain area, it is important to include other input or refined data such as solar radiation measurements and/or cloud cover data. As Dubayah and Rich [1] stated: *Spatial variability caused by clouds can overwhelm the topographic variability caused by even the most rugged terrain* ….

Actual solar radiation estimation is of considerable interest in sustainable environmental and resource planning. Increase in greenhouse gas concentration has caused many governments to explore renewable energy sources [43]. Serbia ratified the Kyoto protocol in 2007 thereby taking responsibility to increase the portion of energy produced from renewable energy, which includes biomass, geothermal, solar, and wind power sources. Thus far, the utilization of renewable energy in Serbia is based mainly on hydro-power plants and biomass to small proportion. According to [44], the solar energy potential in Serbia is estimated to 0.64 million tons annually. The territory of Serbia is favorable in terms of the amount of sunshine hours, being among the highest in Europe [44]. However the extent of utilization of solar panels in Serbia is very limited. Having considered the potential of the country in solar energy usage, this type of energy production should be subsidized through different projects and initiatives.

Acknowledgment

This paper was realized as a part of the project "Studying climate change and its influence on the environment: impacts, adaptation and mitigation" (III 43007) financed by the Ministry of Education, Science and Technological Development of the Republic of Serbia within the framework of integrated and interdisciplinary research for the period 2011-2014. The study was also supported under grants No. III 47014, and TR 36035.

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Paper submitted: April 30, 2015
Paper revised: August 19, 2015
Paper accepted: August 27, 2015