Proceedings of the Pakistan Academy of Sciences: B
Life and Environmental Sciences 60(3): 489-496 (2023)

ISSN (Print): 2518-4261; ISSN (Online): 2518-427X
http://doi.org/10.53560/PPASB(60-3)859

Pakistan Academy of Sciences

Research Article

Geoinformatics and Extrapolation-based Applications for Estimation of Shortwave Radiation Potential as a Sustainable Energy Source: Emphasis on Smart Cities

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Abstract: Smart cities are objectively developed for a sustainable and better life quality for their inhabitants. The present study is focused on the determination of downward shortwave radiation potential-based sites to develop smart cities based on the suitability and useable aspect of these radiations as a sustainable energy source. The downward shortwave radiation is estimated through MTCLIM-XL extrapolation with further spatial-based potential through spatial analysis of Geographic Information System (GIS) as a Geoinformatics application an applicable tool of Geoinformatics majorly helps in integration and processing of related geo-data and related critical factors for final visualization towards smart and applicable decision making. Hence, these properties make Geoinformatics a viable approach in the applications of sustainable energy estimation for the development of smart and sustainable cities. Prospectively, Geoinformatics with the integration of related critical parameters can be a reliable approach for application in the determination of suitable locations for harvesting the radiation potential as a sustainable energy source.

Keywords: Smart cities, Downward shortwave radiation, Sustainable energy, extrapolation, Geographic Information System, Geoinformatics

1. INTRODUCTION

The term "city" has its manifestation since ancient times (3500 to 3000 BC) and relates to the urban set-up and infrastructure based on certain legal terms. Since its basis, this term is changing progressively as the urban infrastructure has evolved due to urban population growth [1]. The United Nations (Department of Economic and Social Affairs) has estimated that by 2050, 68 % of the population will be residing in cities as, according to 2018 data, it has been calculated as 55 % of the global population [2]. Consequently, due to this large and exponential urban population, the consumption of energy resources is leading to challenges of environmental consequences. In addition, there will be a rise in major contributors to the degradation of the urban environment, particularly greenhouse gases (GHG) emissions [3]. In the last three decades, the concept of a 'Smart City' has emerged with a basis of enhancing the life and environment of the growing urban population. In this perspective, to consider ISO 17742 [4], the addition of green and renewable energy resources is an applicable and progressive approach towards the development of a 'Smart City'.

For a viable use of these energy resources, the determination of resource potential is significant to exploit it sustainably within urban infrastructure. For these integrative approach-based studies, geoinformatics is an applicable tool as it integrates

Received: February 2023; Revised: May 2023; Accepted: June 2023
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and processes spatiotemporal data required for the planning and designing of urban infrastructure. For integration as a renewable energy source for 'Smart Cities', the downward shortwave radiation (from herein: DSR) is one of the active and sustainable considering factors, and also essential for the energy systems [5].

These radiations, as an incident flux comprise 85 % of solar radiation, which is a major energy source that drives many critical processes related to energy and agricultural systems [6]. However, there is a challenge in its viable applications due to its intermittent nature, as well as, spatiotemporal and geographical variability. Hence, for its possible total harvesting and determination, the best decision tool is Geoinformatics.

Geoinformatics, including Geographic Information System (GIS), has the applicable ability to smartly manage, and retrieve spatial-based results and thus help in potential-based planning of the feasible locations (hotspots) and areas for harnessing the energy potential. This study proposes and reviews the integrative applications-based role of GIS, a geoinformatics tool, in the determination of DSR potential as an active solar energy source.

2. MATERIALS AND METHODS

2.1. Sustainable Exploitation of the DSR

For better and sustainable exploitation of the radiation energy for different purposes, its determination approach can be based on different phases including; Strategic layout-based estimation, geographical factors-based suitability, technical-based hotspots determination, and utilizability-based potential estimation, respectively. Concisely, for better and sustainable exploitation of the DSR as an active energy resource, the following top-down approach can be applicable.

2.1.1. Strategic layout-based estimation

The Strategic layout-based estimation is the start-up and comprehensive phase in which need and availability-based analysis can be followed to determine the availability and exploitation of resources in a focused area. For instance, the parameter to be considered as an energy resource is the DSR. Hence, the higher the DSR budget against relative need-based usage in the area, the higher will be the sustainable-based potential.

2.1.2. Geographic factors-based potential

The geographic factors-based potential is the analysis of potential after determining the locations where radiation energy can be exploited after consideration of physiographic factors. It entails the exclusion of areas with topographical constraints in the perspective of the best possible exploitation of radiation as an energy resource. These critical physiographic factors includ elevation, slope, and aspect, East and West horizon (which truncate direct irradiance). The solar zenith angle (SZA) can be considered as an additional factor as it has an inverse relation with the downward radiation of the sun (due to radiation decrease) with a rise of SZA.

Furthermore, other geographic constraints also need to be included for consideration of energy potential at the urban level. These include complex urban infrastructure, irregular terrains with high elevations, eco-diverse places including water bodies, etc. as well as, the proximity level towards the grid (base station).

2.1.3. Utilizability-based potential

The Utilizability based potential is the technical-based potential of available DSR in a target area which is based on the conversion of this radiation energy for multi-purposes i.e., electricity generation, thermal insulation of houses, etc. For the radiation to electric power conversion, the downward radiation can be harvested more efficiently during the 'peak sun hours (PSH). PSH refers to the determination and comparison of the amount of sunlight in different locations in any area or region. For instance, 1 PSH is an average of 1,000 watts (W) of energy per square meter i.e., W/m^2.

2.1.4. Utilizability-based potential

The determination of utilizable-based radiation potential gives insights and a realistic approach toward the economic potential. The factors which are critical to be considered include; land types and use, the overall set-up-based cost, and other required infrastructure, as well as, the cost for the maintenance of set-up which may vary according to the applications of DSR energy for certain purposes. In addition, it can also include the related social, economic, and environmental factors of the urban area to be developed.

2.2. Data Acquisition

The incoming shortwave radiation is available only during the daytime, hence, dominates the overall radiation budget. However, these radiations have variations which are based on the amount of its direct and diffuse components having major hindering factors including atmospheric conditions and related topographic agents. On this, Angelis *et al.* [7] followed separate approaches for the determination of both direct and diffuse radiation. These approaches include the acquisition of field data from the meteorological base stations in the target area, as well as, filling the data gaps by different interpolation techniques. Subsequently, the satellite imagery-based data is obtained from MeteoSat (meteorological Satellite). Lastly, these approaches are integrated by using the imagery data for locations having no meteorological stations [7].

In the latest model approach for DSR simulations, particularly in a clear-sky condition, the atmosphere, and terrain-based algorithms retrieve good results for areas with pre-determined metrological data. Additionally, in the last decades, approaches that consider critical topographic factors have also been studied. In these models, some have been integrated as a built-in application in GIS software. However, many such models are based on a common radiative transfer approach which makes their applications unreliable [8].

In the context of solar radiation as an energy resource, Korfiati *et al*. [9] have applied the irradiance data for the determination of photovoltaic cost and its global energy potential. The data was acquired from the NASA database of surface meteorology and solar energy. Similarly, with the GIS-based analysis approach, Sun *et al*. [10] have determined the potential of photovoltaic cells with a focus on Fujian Province, China. For instance, the surface DSR and other related parameters have been derived from geostationary satellite observations [11]. Additionally, Moderate-resolution Imaging Spectroradiometer (MODIS) has also developed datasets of atmospheric parameters which is helpful for the estimation of surface shortwave radiation [12].

The developing trend of climatic and local topographic factors integration is critically significant for the generation of updated spatiotemporal data. Focusing on the estimation of DSR in particular, the impetus for integrating physiographic agents of a focused area has developed as a reliable approach on a local and regional scale. In this context, the MTCLIM (mountain climatic) model has been developed in 'Visual Basic for Applications' to determine the daily-based DSR and other microclimatic variables. The MTCLIM-logic works on extrapolation of daily available local meteorological data inputs from one or two base sites (stations) to a remotely located target site.

2.3. Data Processing

The DSR potential is initiated through DSR determination of the target area by integrating its results from MTCLIM-XL, topographic analysis, and production of the spatiotemporal-based maps in ArcGIS. The significance and reliability of MTCLIM are due to the relative convenience of its basic parameterization, as well as, the easy and fast processing of the modules embedded in the MS-excel-based workbook (version 4.3XL) [13]. The MTCLIM-XL takes into account the basic topographic factors including elevation, slope, aspect, and East/West horizon, as well as, daily weather observations; maximum and minimum temperatures, and precipitation.

In the context of the proposed study [from 5], topographic factors were mainly produced by the available high-resolution imagery of 'Shuttle Radar Topography Mission (SRTM)'. For the initialization file of the MTCLIM-XL, required physiographic information (latitude, elevation, slope, and aspect, East and West horizon of target sites, and elevation of reference site (base station) were generated in GIS environment (Arc GIS 10.1) using 'Spatial analyst' tools. For this process, open-access data of the digital elevation model (DEM) available at high-resolution (30 m) was obtained from the Shuttle Radar Topography Mission (SRTM) [14]. From these generated data layers, the cell-based elevation, slope, and aspect were extracted to the study area-based target points. Finally, spatial layers of the points-based (sites) with physiographic information (slope, aspect, and spatial elevation gradient) of the study area were generated.

Once the DSR is spatiotemporally estimated, the strategic layout-based potential is determined through the production of spatial potential-based hotspot maps of the locations within the target area i.e., the city. Furthermore, the process of geographic factors-based potential follows a similar approach to exclusion-based criteria of the topographical constraints mentioned in section 2.2.

For estimating the utilizability-based potential of the DSR for specific applications, for instance, 250 W/m^2 (Watt per square meter) or 2 kW h/m^2 per day on sites or areas in a city are considered as the radiation-based hotspots with a minimum or exceed that range of surface radiation as a threshold level of any particular energy system [5].

For the source of energy and related applications, the determined radiation (W/m^2) values can be converted into a unit of kilowatt-hour per meter square area (kW h/m^2/day) by using the conversion formula, as given in Eq. (1):

$$E\ (kWh) =\ P\ (W) E(kWh) = P(W) \times \frac{t(hr)}{1000}\ as\ E = kW.\frac{h}{m2}\ Or, E = \frac{\frac{kWh}{m2}}{day} \quad (1)$$

'E' is the DSR energy potential (in Kw: kilowatt) on locations of focused area in square meter (m^2) and time 'h' (hours/day) available as a maximum daily mean 8 hours (considered as maximum peak or active sun-hours on daily mean based). For urban areas with complex topography, a spatial-based factor of the Hill-shade analysis may be considered for the local topographic effects on the DSR budget. Within the Arc GIS environment, the 3D Analyst tool can be applied to generate a shaded relief (from surface raster data) on any specified location [5].

Subsequently, the last level of the proposed approach, economic potential entails the production of a hotspot map which is assessed on the basis of the DSR spatial distribution that can be exploited in specific locations or areas of the target city. These spatial findings lead to a reliable analysis of the exploitable energy, hence; an economical layout can be produced for sustainable applications in the perspective development of a 'Smart city'. Thus, the overall approach is an applicable source of prospective framework and guidance for urban planners and decision-makers for prioritizing this renewable energy source towards sustainable development of urban infrastructure i.e., a smart city.

3. RESULTS AND DISCUSSION

The resultant spatial product of the presented approach of potential determination produces DSR spatial distribution-based maps which provide a clear result for 'need and availability-based analysis. To assess the potential of DSR spatial distribution, a spatial hotspot-based map of the target sites was generated. The next phase of the present approach entails the production of the geographic factors-based potential of DSR spatial distribution which is based on the exclusion criteria of physiographic factors i.e., shaded relief (with local horizon). Subsequently, technical-based potential maps are produced which are based on the utilizable potential of available DSR in a focused area. The utilizability-based potential map was produced based on the conversion of this radiation energy for multi-purpose applications. For instance, in the case of Quetta city, Pakistan, spatial hot-spots analysis depicts some locations including Hazar Ganji, Tor Shor, Hazar Ganji-Chiltan national park, and Chiltan reserved forest with a DSR potential above the threshold level of 2 kW h/m^2/day (Figure 1 and 2). Additionally, the potential of DSR (watt/m^2) every month (for instance, September), and the spatial variations-based hotspots were also derived from daily mean-based data (Figure 2) [5].

Finally, for economical-based potential the correlated analysis-based studies of the focused city i.e., urban planning and management which includes many critical factors including land types and use, and the proposed set-up-based cost which may vary according to the DSR as an energy source for particular purposes. However, in this study context, it is out of approach due to the variations in the cost-benefit analysis of renewable energy exploitation-based projects.

The spatial assessment-based final visualization in maps of the overall and utilizable potential of the DSR estimation produces reliable directions

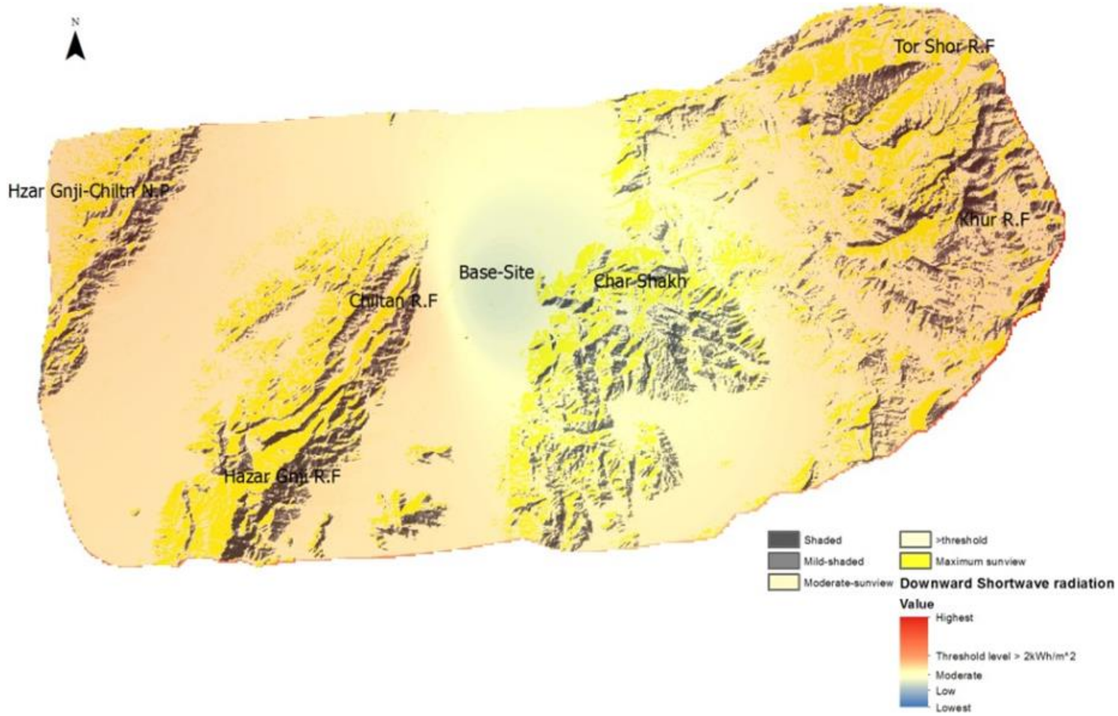

Fig. 1. Potential of DSR on basis of spatial distribution (Quetta city, Pakistan, Year: 2015) Source: Sardar *et al*. (2017) [5]

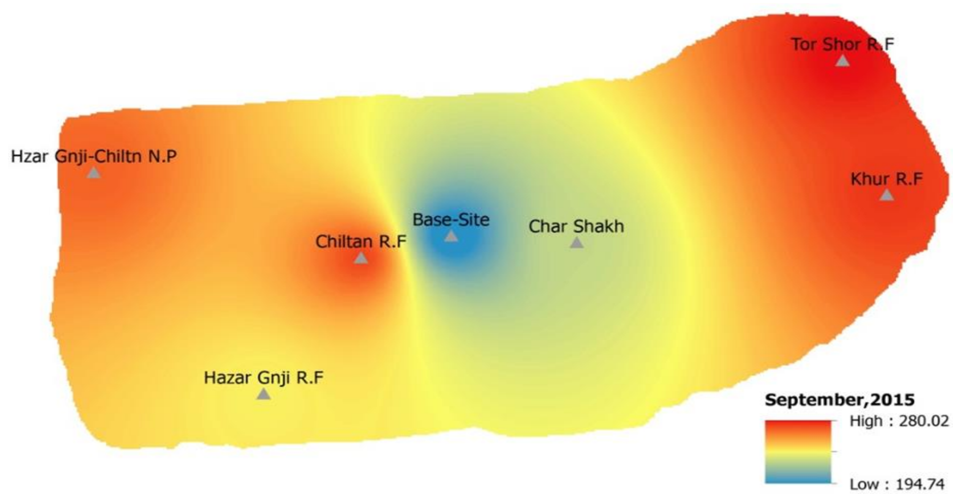

Fig. 2. Spatial distribution-based potential of DSR on target sites (monthly mean basis) (Quetta City, Pakistan, September 2015) Source: Sardar *et al*. 2017 [5]

for urban planners, developers, and policymakers toward the prospective initiation and development of smart and environmentally sustainable cities. For a prospective approach, the numerical-based results of daily mean DSR from MTCLIM-XL in this approach within a GIS environment can be developed as an integrated approach within advanced simulations for smart and updated access to multi-purpose exploitation of this active energy source.

3.1. Data Validation and Analysis on a Spatial Basis

The Daily mean incoming (downward) shortwave radiation (W/m^2); SIS from MeteoSat second generation data (obtained from EUMETSAT's Satellite Application Facility on Climate Monitoring (CMSAF) [15] was used for validation-based assessment of the MTCLIM-XL calculations of the daily mean DSR (W/m^2). This data (CMSAF) was in NetCDF-file format (under MSG-Operational products covering full disk with a daily mean basis of temporal resolution and spatial resolution). From the obtained radiation data in NetCDF files, the EverVIEW-Data viewer [16] was used for retrieval and visualization of data values. Resultantly, a spatiotemporal data set of daily-based DSR was generated for the study data (Year 2015) (Fig. 3) [5].

The validation of the resultant data (daily mean: monthly average of the study year 2015) was carried out on a comparative analysis basis with the obtained data (from CMSAF). For this purpose, root mean square analysis (RMSE) has been proven to be a simple and reliable approach for the evaluation of differences between known and determined data values [17]. The RMSE-based comparative analysis resultantly shows low values for the base site and Char Shakh as compared to other target sites (Table 1). Due to the variable trend in estimated values of radiation for some sites, in contrast to its normal rise with the local change in weather during a year, variations in RMSE values for radiation is common and expectable. In addition, the satellite data can fluctuate from 10 to 50 W/m^{2,} particularly at irregular terrain surfaces with maximum anomalies of up to 600 W/m^2 [18]. For the study data (Year 2015), a relatively high correlation was found between the values of the base site, and Char Shakh site with correlative analysis to the standard data (CM SAF) as shown in Table 1. For Tor Shor reserved forest site, relatively negative values of correlation coefficient were analyzed for three months of data: January -0.23, April -0.35, and May -0.26. However, an agreeable

Fig. 3. EverVIEW Data Viewer (EU METSAT CMSAF) on study area and region-based spatial overlay based tabulated data: highlighted cells of the radiation data (September, 2015) Source: Sardar *et al*. 2017 [5]

Table 1. Root mean square errors (RMSE) between result-data (DSR: W/m^2) and CMSAF (Shortwave radiation products) for Study sites (Year 2015) (Source: Sardar *et al*. 2017) [5]

Site	January	February	March	April	May	June	July	August	Sep.	Nov.	Dec.
Base-station	3	2.89	3.19	4.08	3.99	4.46	3.93	3.94	4.13	3.44	3.04
Char Shakh	2.77	2.74	3.5	3.34	3.46	3.29	3.19	2.85	3.24	2.9	3.06
Tor Shor reserved forest	6.13	5.01	5.15	3.75	3.47	3.6	3.3	2.41	2.21	3.52	4.64
Khur reserved forest	7.4	5.56	5.24	3.62	3.64	4.04	3.52	2.81	2.33	3.91	5.32
Chiltan reserved forest	6.1	4.82	4.75	3.47	3.2	4.04	3.61	2.5	2.32	3.37	4.52
Hazar Ganji reserved a forest	6.95	4.99	4.63	3.42	3.95	4.79	4.21	3.59	3.15	3.52	4.21
Hazar Ganji-Chiltan national park	7.66	5.55	4.85	3.38	3.72	4.47	3.9	3.09	2.46	3.86	5.42

correlation was found for the data of other months [5].

4. CONCLUSION

The proposed integrated-based application of geoinformatics with extrapolation is a reliable and applicable approach for spatial-based determination of solar radiation, particularly DSR, as a sustainable energy source. For better exploitation of this renewable energy resource, the GIS-based approach is relatively significant in spatial visualization of energy for the identification and assessment of potential locations (hotspots) in city areas to assist urban planners and developers. Prospectively, the initiation of these renewable energy resources-based developments will lead to a sustainable and green energy fraction within urban infrastructure. Furthermore, in an economic context, it will be a smart alternative and additive energy supply to meet the growing demand for power consumption in urban areas. In accordance with the 'Goal 7 and 11' of the Sustainable Development Goals [19], such an approach will be an applicable step and standard for smart city development.

The spatiotemporal-based assessment of DSR also require the exclusion criteria of physiographic factors to be considered due to their variations, hence; retrieval of high-resolution data is critical. Furthermore, in the context of energy applications, the reliability of the DSR potential estimation significantly relies on updated spatiotemporal data of major meteorological parameters from sophisticated databases. We anticipate that integration of local physiographic analysis with an interpolation approach, the present study will be applicable for researchers and decision-makers toward real-time assessment of DSR for the potential exploration of potential in areas with sparse or no ground data. Conclusively, this approach will be insightful for the analysis of exploitable energy sources in the perspective development of a smart city. Hence, the determination of the real-time based potential of the DSR in any such area will lead to an alternative, green, and sustainable energy solution.

5. ACKNOWLEDGEMENTS

The corresponding author is thankful to the KUST University, Kohat 26000, Pakistan for providing a research-oriented environment.

6. CONFLICT OF INTEREST

The authors declared that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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