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Utilizing Geographic Information Systems Techniques to Study Solar Radiation Variations in Iraq for the Period (2008-2022)

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Abstract

Calculating net solar radiation (R_n) is of great importance in various fields, including agriculture, the environment, and industry. Several methods are used to calculate R_n , including the direct method (composite net solar radiation (CNR4)) and the indirect method using several empirical equations that depend primarily on temperature and astronomical location. The primary objective of this research is to calculate and evaluate changes in net solar radiation values for Iraq during the period 2008-2022, using several variables such as (R_{nl} , R_{ns} , R_{so} , R_s , R_a , and e_a). The secondary objective is to determine the nature of the relationship between R_n and T_{max} .

The results showed that R_n values in the northern regions of Iraq are consistently lower than in the central and southern regions, due to Iraq's high latitude and continental climate. The criterion R_n for Iraq was determined by averaging the most appropriate values from the studied stations that cover Iraq approximately equally. The year 2013 recorded the lowest solar radiation readings, while 2021 recorded the highest. Furthermore, this work demonstrates that net solar radiation controls daytime air temperature and is a major contributor to the temperature increase in Iraq, as every change in R_n behavior is accompanied by a corresponding change in T_{max} . The results showed a positive linear relationship between R_n and T_{max} .

Keywords: Temperature, climate change, Inverse Distance Weighting, WANA region

استخدام تقنيات نظم المعلومات الجغرافية لدراسة التغيرات في الإشعاع الشمسي في العراق للفترة (2008-2022)

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الخلاصة

إن حساب الإشعاع الشمسي الصافي (R_n) له أهمية كبيرة في العديد من المجالات، مثل الزراعة والبيئة والصناعة. وتستخدم عدة طرق لحساب R_n ، بما في ذلك الطريقة المباشرة (الإشعاع الشمسي الصافي

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المركب (CNR4) والطريقة غير المباشرة باستخدام عدة معادلات تجريبية تعتمد بشكل أساسي على درجة الحرارة والموقع الفلكي. الهدف الأساسي من هذا البحث هو حساب وتقييم التغيرات في قيم الإشعاع الشمسي الصافي للعراق خلال الفترة 2008-2022، باستخدام عدة متغيرات مثل (R_n , R_{ns} , R_{so} , R_a , R_s , e_a). الهدف الثانوي هو تحديد طبيعة العلاقة بين R_n و T_{max} . أظهرت النتائج أن قيم R_n في المناطق الشمالية من العراق تكون دائماً أقل منها في المناطق الوسطى والجنوبية، وذلك بسبب الموقع الفلكي للعراق والمناخ القاري. تم تحديد معيار R_n للعراق من خلال أخذ متوسط القيم الأكثر ملاءمة للمحطات المدروسة التي تغطي العراق بشكل متساوٍ تقريباً. سجل عام ٢٠١٣ أدنى قراءات للإشعاع الشمسي، بينما سجل عام ٢٠٢١ أعلى قراءات. علاوة على ذلك، يُظهر هذا العمل أن صافي الإشعاع الشمسي يتحكم في درجة حرارة الهواء نهائياً، وهو مسبب رئيسي لارتفاع درجة الحرارة في العراق، لأن كل تغيير في سلوك R_n يتبعه تغيير في T_{max} . أظهرت النتائج علاقة خطية موجبة بين R_n و T_{max} .

1. Introduction

Net solar radiation (R_n) is equal to the difference between fluxes of the net short-wave radiation and the net long-wave radiation [1]. Solar irradiance is essential in several aspects, including earth science, agronomy, engineering geotechnics, and ecology. The study of the overlap between soil, plants, and the atmosphere depends on net solar radiation [2,3]. It is necessary for many chemical and physical processes, such as photosynthesis, evaporation, and transpiration [4,5,6]. There are three types of factors that affect the value of R_n ; the first type is the climatic factor (rain, fog, dust, and particles suspended in the air, including carbon dioxide particles, natural or man-made reference smoke, and relative humidity)[7,8,9,10,11], the second type is astronomical factors which include solar declination angle, duration of sunshine, solar hour angle, solar flare angle, elevation, albedo), the third type is topographic factors which include mountains, vegetation cover, and water surface levels)[12,13,14,15]. Numerous studies have been conducted in this field in Iraq. Waleed I. et al. (2009) stated that the objective of the study was to calculate net radiation on a horizontal surface for the years 1980–2002, using data from three stations: Mosul, Baghdad, and Nasiriyah. The results showed that the two calculated and measured solar radiation matched, where the values of (M. A. E) are (24, 14, 11) % in Mosul, Nasiriyah, and Baghdad, respectively, showing correlations between R_n and climatic elements (temperature, wind speed, relative humidity, and brightness) [16]. Emad J. et al. (2022) compared the accuracy of solar radiation data from pvGis and ground stations. The Comparison showed that ground stations are better, as significant differences in some curves from dawn to sunset. There is a difference in the solar radiation station rates due to its location [17]. Despite numerous studies in this field, the relationship between net solar radiation (R_n) and maximum temperatures (T_{max}) remains unclear, particularly its type (direct or inverse). This research aims to comprehend the causes of variation in net solar radiation values and their impact on temperature values (temperature during the period of solar brightness) and to find a criterion value that represents the rate of net solar radiation for Iraq, the importance of this specific value is to determine the best places to place solar concentrators (point or linear) in Iraq, which are helpful in several areas, including the establishment of solar-electric factories, water desalination factories, and other technologies that rely on solar radiation as its basis.

2. Materials and Methods

Iraq is located in West Asia and North Africa (WANA), overlooking the Arabian Gulf. Iraq's geographical area extends from Longitude ($38^{\circ} 45'$) to ($48^{\circ} 45'$) East and Latitudes ($29^{\circ} 5'$) to ($37^{\circ} 22'$) North, regions most of an arid Iraq climate with scorching summers and little annual precipitation since the amount of rainfall per year is between 250 to 300 mm [18,19,20], Iraq is 438,320 km², of which 21% are made up of water plane surfaces, such as rivers, lakes, and swamps. Figure 1.

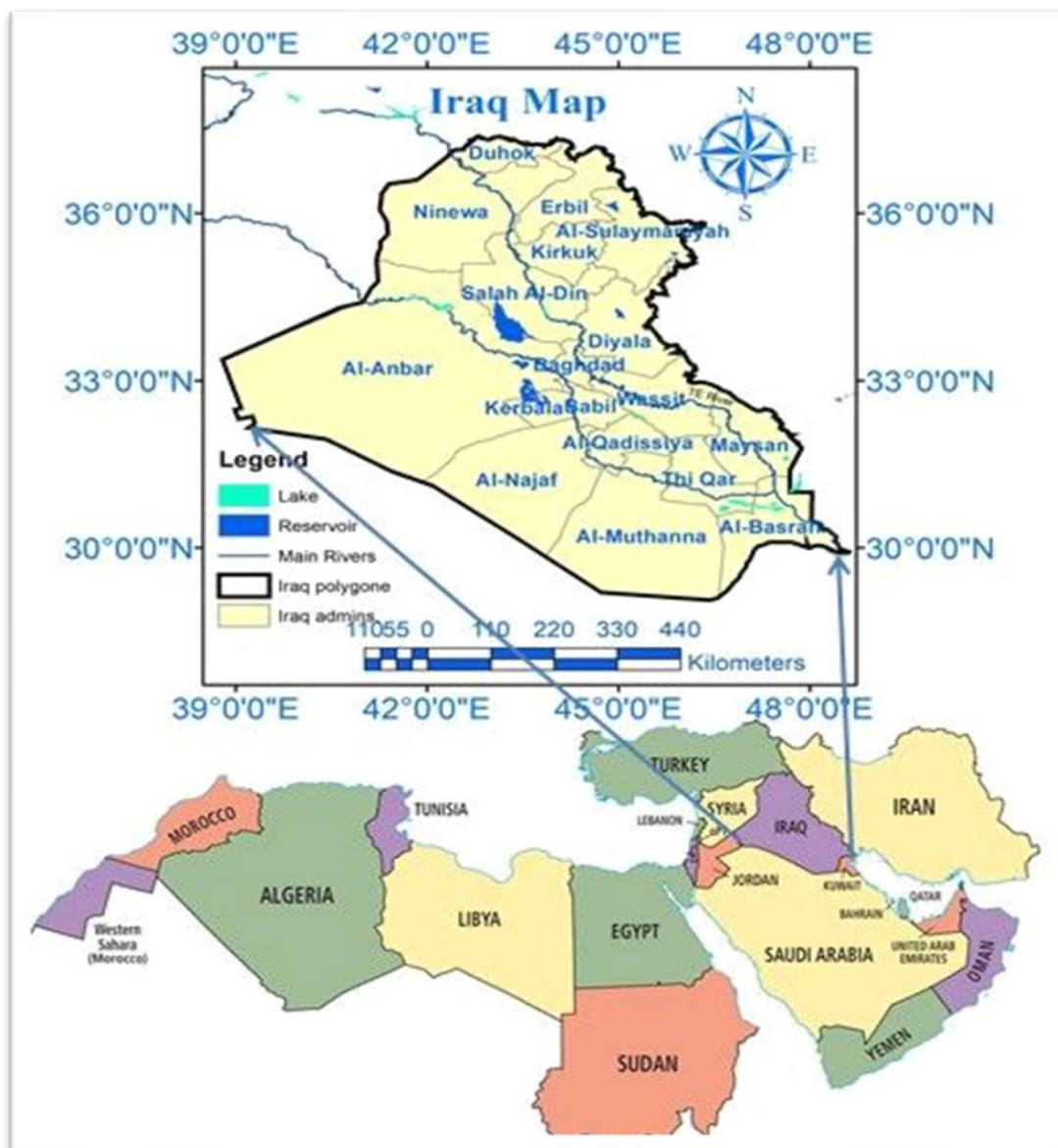


Figure 1: Geographical location of the study area within the West Asia and North Africa (WANA) region

This study relied on data from the Iraqi Meteorological Organization and seismology. Specific meteorological readings were relied upon from 14 selected stations to have a comprehensive distribution to cover the entire area of Iraq for fifteen years, within a time range from 2008 to 2022., Figure 2.

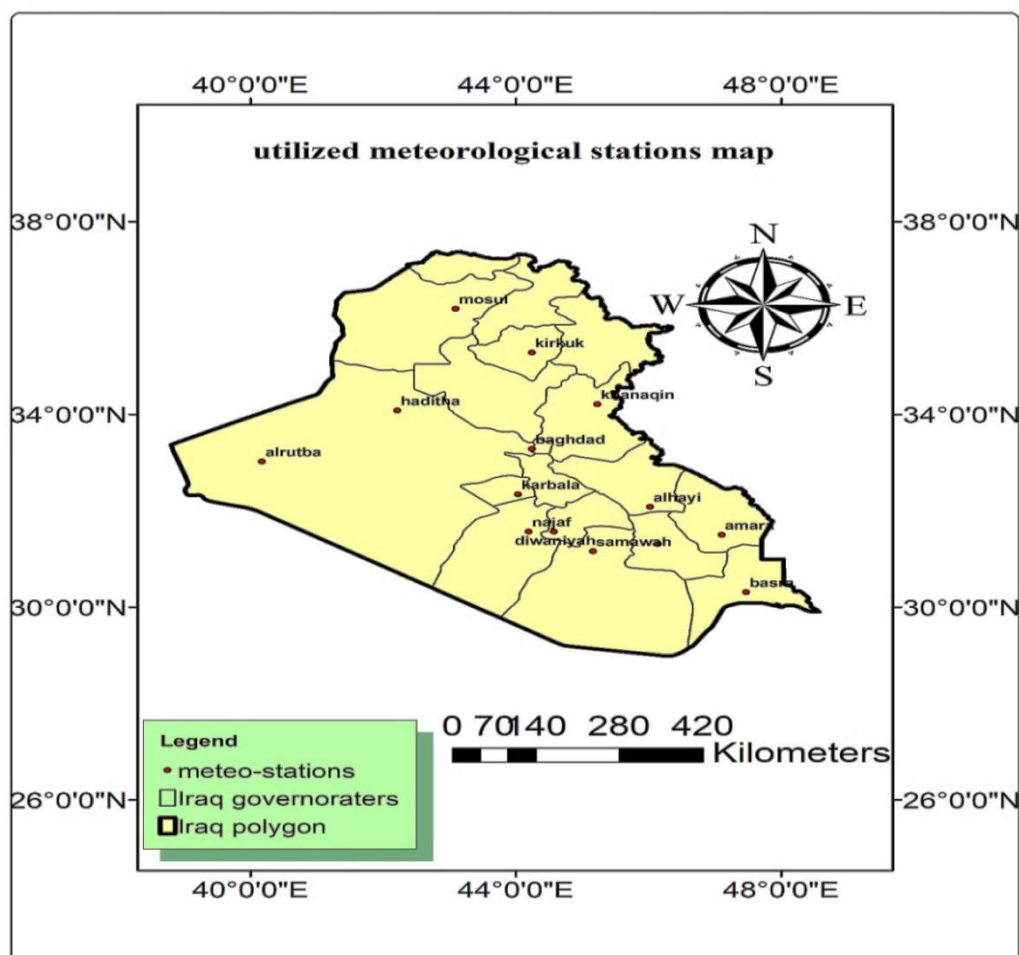


Figure 2: The geographical location map of the utilized meteorological stations in Iraq.

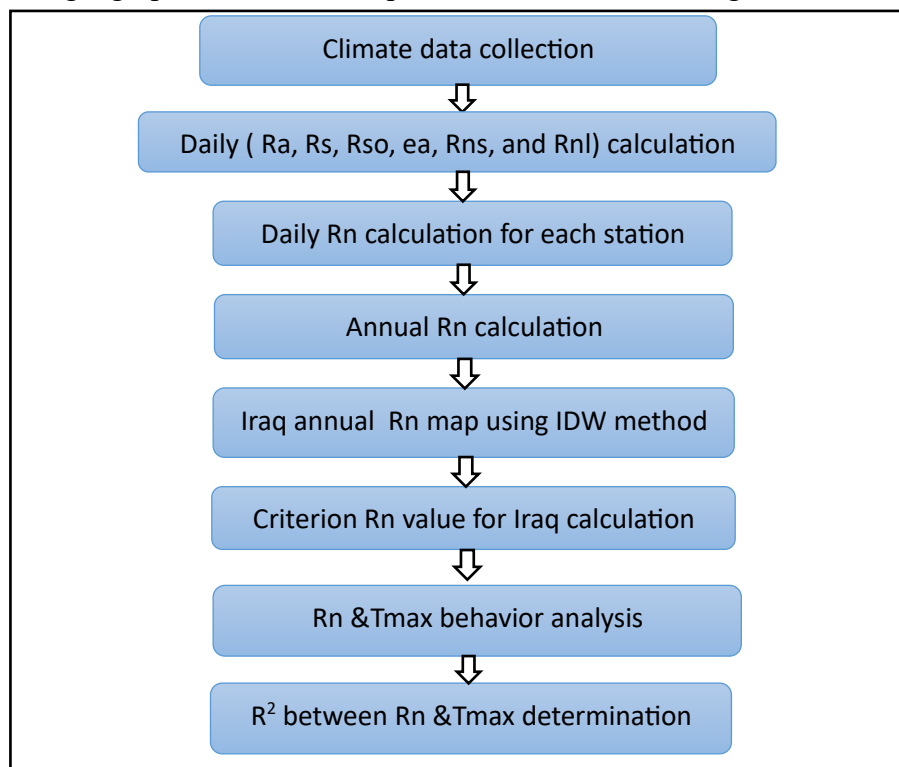


Figure 3: Diagram of the utilized methodology

Net solar radiation can be measured using the four-component net radiometer (CNR4)[21,22]. The second method calculates the net solar radiation experimentally using several equations [23,24]:

$$R_n = R_{ns} - R_{nl}, R_n = (1 - \alpha)R_s - R_{nl} \dots \dots \dots (1)$$

Where:

R_n = Solar radiation at 2 meters above the earth's surface ($\text{MJ.m}^{-2}.\text{day}^{-1}$)

R_{nl} = longwave radiation departs the earth's surface ($\text{MJ. m}^{-2}.\text{day}^{-1}$)

α = The coefficient of solar radiation total reflectance (albedo = 0.23)

R_s = shortwave radiation reaching the earth's surface ($\text{MJ. m}^{-2}.\text{day}^{-1}$) calculated by the following equation:

$$R_s = K_{Rs} \cdot R_a (T_{\max} - T_{\min})^{0.5} \dots \dots \dots (2)$$

where, $K_{Rs}=0.16$

Net long-wave radiation can be calculated using the following equation[25,26]:

$$R_{nl} = \left[\frac{(T_{\max,k}^4 + T_{\min,k}^4)}{2} \right] (a_l - b_l \sqrt{e_a}) \left[a_c \frac{R_s}{R_{so}} - b_c \right] \dots \dots \dots (3)$$

Where:

σ = The constant of Stefan-Boltzmann ($4.903 \times 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ day}^{-1}$)

$T_{\max}$ = The temperature maximum

$T_{\min}$ = The temperature minimum

e_a = Actual vapor pressure (kPa)

(a_l , b_l , a_c , b_c) = calibration coefficients dimensionless respectively (0.34, 0.14, 1.35 and ,0.35)

R_{so} = sun radiation in the clear sky ($\text{MJ m}^{-2} \text{ day}^{-1}$),

R_{so} is calculated using the equation[27]:

$$R_{so} = (0.75 + 2 \times 10^{-5} \cdot h) \cdot R_a \dots \dots \dots (4)$$

Where:

h = elevation of the surface above sea level (m)

R_a = Solar radiation outside the atmosphere ($\text{MJ. m}^{-2}.\text{day}^{-1}$),

R_a is obtained from the equation[28]:

$$R_a = \left(\frac{24}{\pi} \right) G_{sc} d_r [\omega_s \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega_s)] \dots \dots \dots (5)$$

Where:

G_{sc} = constant solar radiation reaching the earth [$4.92 \text{ MJ.m}^{-2}.\text{h}^{-1}$]

d_r = Earth-Sun inverse relative distance

ω_s = Hour angle at sunset [rad]

ϕ = latitude [rad]

δ = solar deviation [rad]

The Earth-Sun inverse relative distance is obtained from the equation:

$$d_r = 1 + 0.033 \cos\left(2\pi \frac{J}{365}\right) \dots \dots \dots (6)$$

The solar radiation deviation is obtained from the equation:

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \dots \dots \dots (7)$$

Where:

J = is any day of the year from (1 to 365 and/ or 366)

The converted latitude in degrees to radians is:

$$\text{Radians} = \frac{\pi}{365} \times \text{degrees latitude} \dots \dots \dots (8)$$

The sunset hour angle is obtained from the equation:

$$\omega_s = \arccos[-\tan(\phi) \tan(\delta)] \dots \dots \dots (9)$$

The equations used to determine R_n are daily measurement equations that apply from January 1 to December 31, converting the average monthly meteorological reading into a daily reading. Other equations were calculated to find R_n , which are: (R_a , R_s , R_{so} , e_a , R_{ns} , and R_{nl}).

Table 1: is an example of calculating daily variables to determine the value of Rn for Mosul Governorate on January 1, 2008.

Dr	Φ	δ	ws	Ra	Tma _x	Tmi _n	Rs	Rso	ea	Rns	Rnl	Rn
1.032 9	0.631 6	- 0.40 1	1.255 3	16.191 6	12	-2.2	9.762 3	12.215 9	0.519 8	7.51 7	5.115 2	2.401 8

After calculating these previous equations, daily Rn results were obtained, and then the average annual Rn values were calculated for each year at all 14 stations in Iraq. The annual Rn values for 2008, 2013, 2018, and 2022 are illustrated in Table 2.

Table 2: The annual average Rn values for the meteorological stations studied in Iraq (2008, 2013, 2018, 2021, and 2022)

Station	Longitude (Des.deg.)	Latitude (Des.deg.)	2008's Rn (MJ.m ⁻² .year ⁻¹)	2013's Rn (MJ.m ⁻² .year ⁻¹)	2018's Rn (MJ.m ⁻² .year ⁻¹)	2021's Rn (MJ.m ⁻² .year ⁻¹)	2022's Rn (MJ.m ⁻² .year ⁻¹)
Mosul	43.09	36.19	10.236	10.117	10.286	10.307	10.191
Kirkuk	44.24	35.28	9.8185	9.9595	9.9553	10.565	10.215
Knanaqin	45.23	34.21	10.667	10.796	10.917	11.204	10.991
Haditha	42.21	34.08	10.356	10.195	10.238	10.875	10.752
Baghdad	44.24	33.28	10.917	10.543	10.781	11.062	11.033
Alrutba	40.17	33.02	10.302	10.046	10.250	10.587	10.469
Karbala	44.03	32.34	10.670	10.518	10.715	11.054	10.932
Alhay	46.02	32.08	10.762	10.593	10.808	11.376	11.158
Najaf	44.19	31.57	11.252	10.694	10.831	11.171	11.071
Dawaniyah	44.57	31.57	11.048	11.004	10.796	11.302	11.254
Amara	47.1	31.5	11.362	10.739	11.208	11.618	11.427
Nasriyah	46.14	31.31	11.374	11.070	11.393	11.616	11.556
Smawah	45.16	31.16	11.179	10.910	11.091	11.487	11.367
Basra	47.47	30.31	11.558	11.098	11.671	11.775	11.700

The next step is to convert each year's annual average Rn value into a point shapefile based on the station location in ArcGIS 10.8. Then, the interpolation process was used using the Inverse Distance Weighted method (IDW) It is a spatial interpolation technique that relies on estimating an unknown value at a given location through a weighted average of known values at neighboring locations, where weights are calculated based on the reciprocal of the

distance raised to a certain power, giving closer points a greater influence in the estimation than farther points, as it mathematically clarified by the following:

$$Z(X, Y) = \frac{\sum_{i=1}^n \left[\frac{Z_i}{d_i^p} \right]}{\sum_{i=1}^n \left[\frac{1}{d_i^p} \right]} \dots \dots \dots (10)$$

$$d_i = \sqrt{(X_i - X)^2 + (Y_i - Y)^2} \dots \dots \dots (11)$$

Where $Z(X, Y)$ is the predicted value at the ensample location X, Y ; i is the number of measured sample points within the neighborhood defined; Z_i is the observed value at location i ; d_i is the distance between the predicted location X, Y ; and p is the power parameter that defines the rate of reduction of the weight as distance increases[29].

In this work, the IDW method was employed to derive parameters that optimize the estimation of radiation distribution across Iraq. These parameters are:

- Data are limited and not dense.
- Data are relatively scattered.
- Lack of a clear spatial pattern.
- Data representation over the entire area is required, so complex statistical analysis, such as Kriging, is not required.
- There are no extreme fluctuations in values between nearby points.

Also, objectively, this method has the lowest root-mean-square difference between measured and predicted values among the methods.

The IDW method was used, as it has the lowest root-mean-square error, to estimate the annual average R_n for 2008, 2013, 2018, and 2021 (Figure 4).

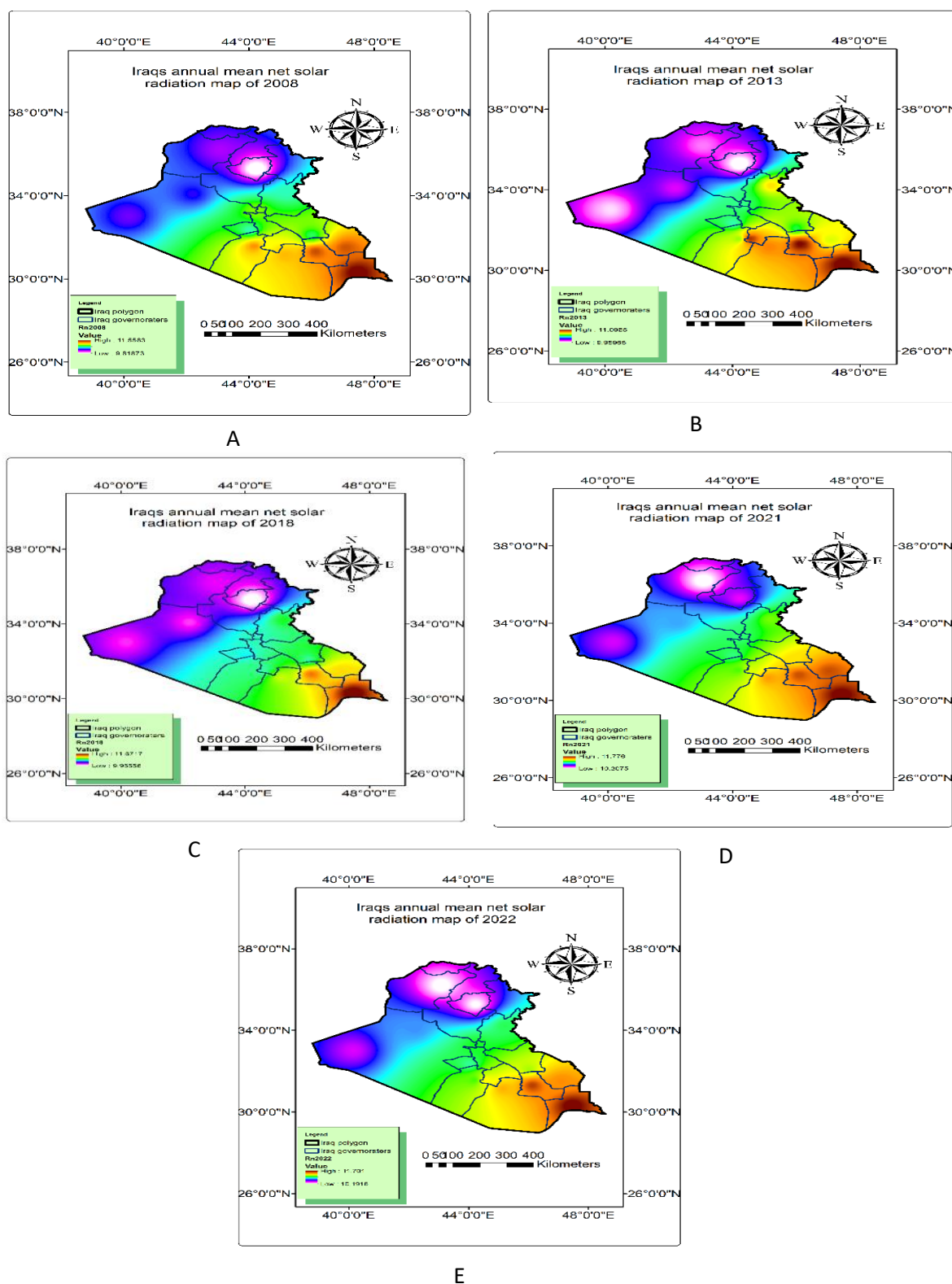


Figure 4: A. The annual average Rn of Iraq in 2008, B. The annual average Rn of Iraq in 2013, C. The annual average Rn of Iraq in 2018, D. the annual average Rn of Iraq in 2021, and E. the annual average Rn of Iraq in 2022.

Variation rate is a statistical measure that expresses the relative change between two values over time. It is typically expressed as a percentage, indicating the direction of change (either an increase or a decrease). It is a crucial tool in climate studies for monitoring changes in key elements, including temperature, rainfall, and solar radiation.

The rates of variation, R_n , and T_{max} will be determined, where the variation rate is [30]:

Variation rate

$$= \frac{\text{New (annual value)} - \text{Old(station stable value)}}{\text{Old(station stable value)}} \times 100\% \dots \dots \dots (12)$$

3. Results and analysis

The stable annual R_n mean value for the studied stations by sum the annual R_n values (2008-2022) for each station and dividing them by 15, which is the number of years, where the results of the values (R_n stable values for stations): Mosul, Kirkuk, Khanaqin, Haditha, Baghdad, Alrutba, Karbala, Alhayi, Najaf, Diwaniyah, Amara, Nasriyah, Samawah, and Basra was 10.18989, 10.05473, 10.92887, 10.45343, 10.83913, 10.26203, 10.80535, 10.97355, 11.02987, 11.14537, 11.24162, 11.42955, 11.20313, and 11.51163, respectively.

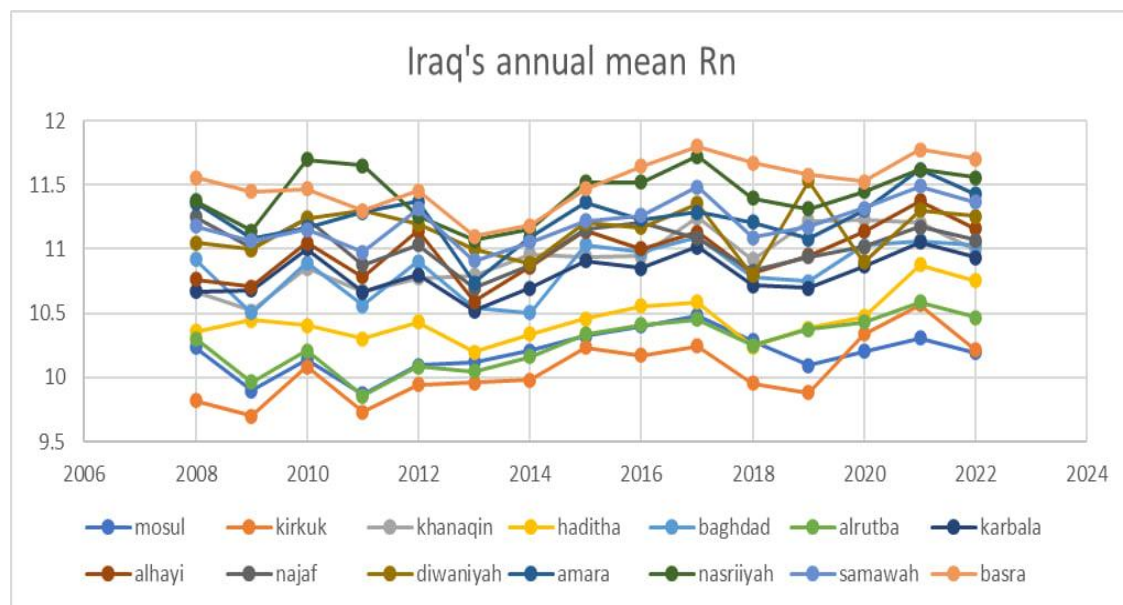
To find a criterion R_n value for Iraq by sum the stable R_n value for all stations and divide on 14 which is the number of stations, R_n value is 10.86201 MJ.m⁻².year⁻¹, where it was noted that the lowest R_n value in 2013 because there are 10 stations whose value does not exceed the criterion's R_n value for Iraq, the highest R_n value in 2021 because there are 11 stations whose value exceed the criterion's R_n value for Iraq.

R_n variation rate value at each station for years 2008 to 2022 [(Mosul (-3.12%_ 2.88%) Kirkuk (-3.51%_ 5.07%), Khanaqin (-3.73%_ 2.90%), Haditha (2.46%_ 4.03%), Baghdad (-3.10%_ 2.33%), Alrutba (- 3.95%_ 3.16%), Karbala (2.09%_ 2.30%), Alhay (-3.46%_ 3.67%), Najaf (-3.04%_ 2.02%), Diwaniyah (-3.13%_ 3.45%), Amara (-4.46%_ 3.35%), Nasriyah (-3.14%_ 2.57%) Samawah (-2.61%_ 2.54%) and Basra (-3.58%_ 2.52%)).

In addition to the influence of greenhouse gases on air temperature, which is considered the second most significant factor, net solar radiation is the primary factor that controls air temperature. Consequently, variations in R_n lead to climate changes, as climate engineering primarily focuses on temperature.

To find the maximum temperature (T_{max}) variation rate value at each station for years 2008 to 2022, (mosul (-6.04%_ 3.40%), Kirkuk (-3.64%_ 5.05%), Khanaqin (-3.50%_ 2.63%), Haditha (-4.03%_ 7.11%), Baghdad (-3.17%_ 1.83%), Alrutba (-5.17%_ 4.74%), Karbala (-4.45%_ 4.26%), Alhay (-4.85%_ 3.59%), Najaf (-3.51%_ -0.23%), Diwaniyah (-0.21%_ 1.97%), Amara (-6.21%_ 6.28%), Nasriyah (-4.20%_ 2.16%), Samawah (-3.67%_ 4.33%) and Basra (-2.97%_ 2.54%). It was noted that the value of R_n in the northern regions is lower than in the central and southern regions, reflecting their astronomical locations in Iraq and their distance from the seas.

A significant similarity was observed between the behavior of net solar radiation and the maximum temperature at all the studied stations, with increases and decreases in R_n values mirroring the behavior of T_{max} , as shown in Figure 5.



A

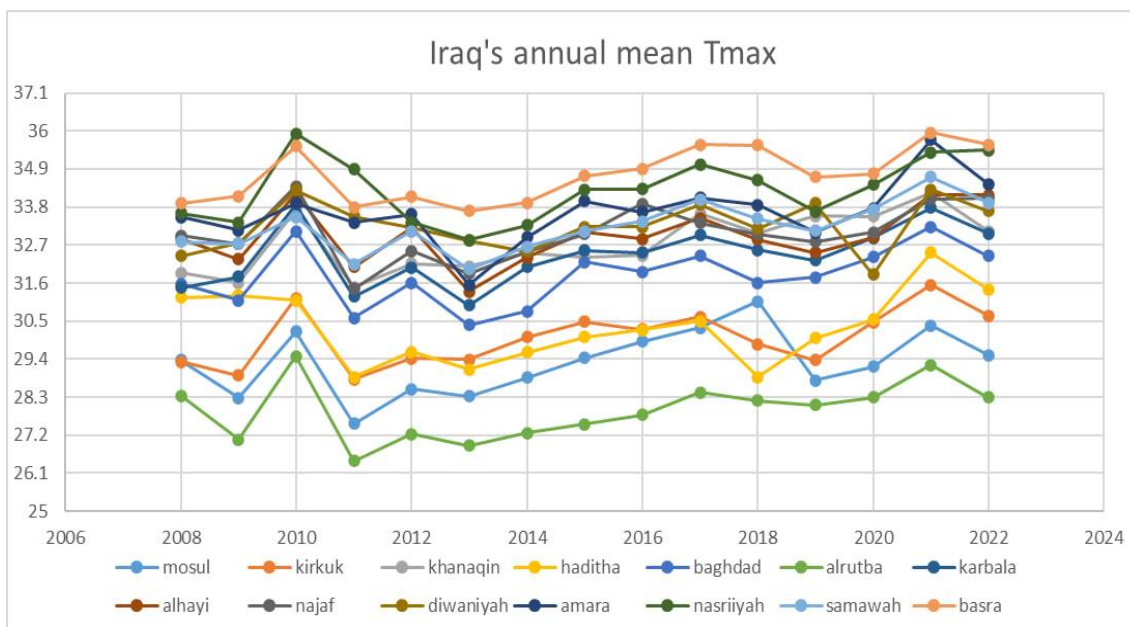


Figure 5: A. Iraq's annual average net solar radiation, B. Iraq's annual average maximum temperature

To state the nature of the relationship between the values of R_n and T_{max} random variables for all the studied stations, the linear correlation coefficient R^2 between them was calculated, Table 3

Table 3: R^2 values range from 0.73 to 0.91, indicating a positive linear to semi-linear correlation between R_n and T_{max} .

Station	Mosul	Kirkuk	Khanaqin	Haditha	Baghdad	Alrutba	Alhayi	Najaf	Diwaniyah	Amara	Nasriyah	Samawah	Basra
R^2	0.85	0.85	0.84	0.79	0.84	0.74	0.91	0.73	0.75	0.91	0.91	0.89	0.80

4. Conclusions

- GIS technology is the ideal choice for mapping, modeling, and simulating solar radiation because it enables the integration of multiple layers of data, allowing for the application of spatial filters to extract radiation patterns in both small and large areas. This technology also includes spatial interpolation tools (such as Kriging or IDW) that fill gaps between measurement stations, resulting in a smooth, difficult-to-divide map. Additionally, it is possible to analyze spatial intersections (overlay analysis) to determine how terrain or land use affects the distribution of radiation.
- In Iraq, the values of R_n in the northern regions are consistently lower than those in the central and southern regions, due to their high latitude and distance from the seas, which make Iraq's climate continental. The southern part is in a hot tropical region, while the northern part is in a warm region.
- During the studied period, the lowest R_n values were observed in 2013 and the highest in 2021 at most Iraq stations.
- This work demonstrated a strong positive correlation between R_n and T_{max} , as net solar radiation warms the lower atmospheric layers.

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