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Integration of Remotely Sensed Digital Elevation Model Data and Geographic Information System Facilities to Estimate Net Solar Radiation Variances in Iraq (1987-2017)

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Abstract

The calculation of potential earth's surface solar radiation is imperative for analyzing the atmosphere-vegetation-soil interaction process. Therefore, many schemes were introduced with direct (using net radiometer) or indirect (using air temperature or air plus soil temperatures) formulas. Three combinations of factors are known to control the R_n value; the astronomical based factors which determine the general spatial distribution of R_n values, the climatological factors which determine the assigned spatial variation of those values, and the topographical factors that influence climatological factors rates (i.e. have indirect effects on Rn values).

For Iraq, the ecosystem influences of global warming were obvious in the 1980s and the R_n rates approached peak values .. Thereafter, the general behavior of R_n rates was geographically-based , i.e. increasing rates in the middle and southern regions and descending rates in the northern parts, since it was spatially correlated in a reverse manner with RH values. In the present study, this issue was clarified by utilizing the standard annual mean Rn rate known for Iraq’s weather, which was 9.8MJ.m^{-2}.year^{-1}. The results showed that, in 1987, the area with annual mean R_n equal or higher than this annual standard rate was 305088.098 km^2. The area was reduced to 241984.77 km^2 in 1997, followed by an expansion to 294491.136 km^2 in 2007, and another reduction to 277272.542 km^2 in 2017.

Keywords: extraterrestrial radiation, relative humidity, global warming, and MENA region

تكامل استعمال بيانات نموذج الارتفاعات الرقمي المستشعرعن بعد مع امكانيات نظم المعلومات الجغرافية لتخمين تغايرات الاشعاع الشمسي الصافي في العراق من (1987–2017)

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الخلاصة

يعد احتساب الشعاع الشمسي المحتمل لسطح الارض امرا ضروريا في تحليل التفاعل بين الغلاف الجوي والنبات والتربة, من هنا تم اقتراح عدة طرق منها مباشرة(باستخدام جهاز قياس الاشعاع الصافي) ومنها غير مباشرة بوساطة معادلات تعتمد على معرفة درجة حرارة الهواء او الهواء والتربة معا بغية تقدير مقدار الاشعاع

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الشمسي الصافي للأرض. يوجد ثلاث مجاميع من العوامل اللاتي تتحكمن بقيمة الاشعاع, العوامل الفلكية المنشأ والتي تحدد التوزيع المكاني العام لقيم ال Rn والعوامل المناخية التي تحدد التغاير المكاني الخاص لكل من هذه القيم والعوامل الطوبوغرافية التي تؤثر على عوامل المناخ (بمعنى تأثيرها غير المباشر على قيم الRn) . اثبت هذا البحث ان التأثيرات البيئية للاحتباس الحراري في العراق كانت كبيرة وبلغت حدها الاقصى في ثمانينيات القرن العشرين. لذلك فان مناسيب الاشعاع الشمسي الصافي وصلت حدودها القصوى عند الثمانينات ثم اتخذ سلوكها منحى ذو مرجعية جغرافية (بمعنى تصاعد هذه المناسيب في مناطق وسط وجنوب العراق وتناقصها في شماله) حيث انها مترابطة مكانيا وبشكل عكسي مع قيم الرطوبة النسبية. هذا الشأن قد تم اثباته باستخدام قيمة معيارية للمعدل السنوي للإشعاع الصافي حسب مناخ العراق هي $9.8 MJ.m^{-2}.year^{-1}$. في سنة 1987 كانت مساحة المناطق التي معدل اشعاعها الصافي مساوي او اكثر من $9.8 MJ.m^{-2}.year^{-1}$ هي 305088.098 km ثم تقلصت الى $241984.77\ km^2$ في سنة 1997 بعدها اصبحت $294491.136\ km^2$ في 2007 وبعد ذلك اضحت $277272.542\ km^2$ في سنة 2017.

Introduction

The determination of potential earth's surface solar radiation (commonly called the net solar radiation R_n) has a great importance in the analysis of the interaction processes of atmosphere-vegetation-soil in many fields, such as soil science, geotechnical engineering, environmental engineering, and agronomy [1, 2]. R_n stands for sun's effective energy that reaches earth's or crop's surface , heats the soil and the surrounding air, and evaporates and transpires the water from the planet [3] . It represents the summation of "short plus long" wave radiation [4]. In any place on the earth, there are factors that interact to build a general pattern of net solar radiation values (i.e. specified spatial distribution of R_n values). These factors include the orbital movement of earth around the sun, that determines weather seasons (i.e. daily sun duration hours), and the geographical location according to latitude circles, which determines radiation incident angle (i.e. radiation path length inside the atmosphere) [5]. On the other hand, there are climatological factors that are responsible for causing variations in Rn spatial distribution. These factors are related to global and regional weather influences [6]. The most important factor is relative humidity (RH), as the near-surface water vapor absorbs, scatters, and reflects huge portions of R_n and contributes to fog, cloud, and rain generation. The value of RH inversely affects solar radiation [7,8]. In addition, climatological and topographical factor have noticeable effects on R_n, since they influence radiation path length in the atmosphere, air temperature, and humidity [9]. R_n could be measured in the field, using a net radiometer after some calibration to a parameter that is known as net radiometer sensitivity, or calculated using many equations that fall into two main methods; the first method merely depends on air temperature [10] while the second depends on both air and soil temperatures [11]. The calculation scheme is preferred because of the measurement errors that range from 10% to 25% of the measurement readings. In this research, the common scheme presented by an earlier study [1] was selected to calculate daily R_n for Iraq in the interval 1987- 2017, utilizing the available meteorological data supplied by the Iraqi Meteorological and Seismic Organization. This scheme stated that:

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

Where:

R_n = net solar radiation (MJ. m^{-2}. day^{-1}),

R_{nl} = net long-wave radiation leaving the earth's surface (MJ. m^{-2}. day^{-1}),

α = radiation reflectance coefficient (albedo = 0.23),

R_s = calculated or measured short-wave radiation that reaches earth's surface plane.

Net long-wave radiation can be calculated using the following equation:

$$R_{nl} = \sigma\left[\frac{(T_{\max}+273)^4+(T_{\min}+273)^4}{2}\right]\left[0.34-0.14(e_a)^{0.5}\right]\left(1.35\frac{R_s}{R_{so}}-0.35\right) \qquad \text{....(2)}$$

where:

σ = constant of Stefan-Boltzmann (4.903 × 10-9(MJ. K^{-4}. day^{-1}),

T_{max}= the maximum temperature,

T_{min} = the minimum temperature,
R_{so}= calculated radiation of the clear sky (MJ m-2 day-1),
The rate of Rs/Rso in Equation (2) will not exceed 1.
Clear sky radiation is determined by:

$$R_{so} = (.75\times 2\times 10^{-5}\, z)R_a \qquad \text{….(3)}$$

where:
Z = elevation in meters above the sea level (for each station acquired from the digital elevation model),
R_a= extraterrestrial radiation (MJ. m^{-2}. day^{-1}),
R_a is stated by:

$$R_a = \frac{24}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \qquad \text{…(4)}$$

where:
G_{sc}= the solar constant = 4.92 (MJ. m^{-2}. h^{-1}),
d_r = inverse of the square of relative Earth to Sun distance,
ω_s = sunset hour angle (radians),
φ = latitude (radians),
δ = solar declination (radians).
The inverse of the square for relative Earth to Sun distance is given by:

$$d_r = 1 + 0.033\cos\left(2\pi \frac{J}{365}\right) \qquad \text{….(5)}$$

where:
J is any day of the year and given by:

$$J = D_M - 32 + Int\left(\frac{275M}{9}\right) + 2Int\left(\frac{3}{M+1}\right) + Int\left(\frac{M}{100} - \frac{Mod(Y,4)}{4} + 0.975\right) \qquad \text{…..(6)}$$

where:
D_M = day of the month,
M= month of the year,
Y= year (4 digits).
The latitude in degrees is converted to radians measurement by:

$$\text{Radians} = \frac{\pi}{180} \times \text{degrees latitude} \qquad \text{……(7)}$$

The declination of solar radiation is:

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \qquad \text{……(8)}$$

While sunset angle is:

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \qquad \text{…..(9)}$$

Study Area

Iraq is one of the WANA (West Asia and North Africa) region countries, which is commonly called MENA region. It lays in the northeastern part of this region, with climate that is described to be arid to semi-arid, as annual rainfall does not exceed 250-300 millimeters. Iraq coordinates are:
Longitudes; (38° 45') to (48° 45')East.

Latitudes; (29º 5') to (37º 22') North.
Its area is 438,320 square kilometers, with 21% constituting water plane surfaces (i.e. lagoons, marshes, and rivers), as shown in Figure-1.

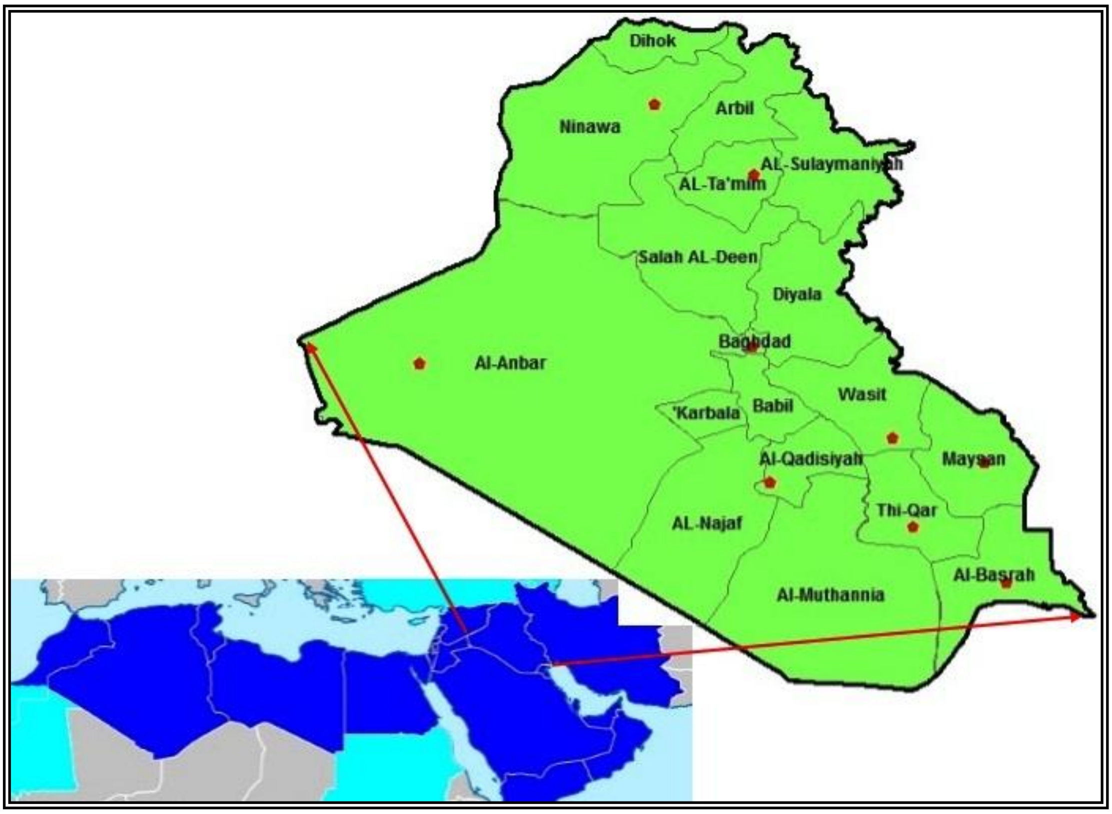

Figure 1- Geographical location of the study area within the WANA region

The green-house gases are known to cause rapidly increment in global warming effects, which become more severe as average air temperature increases, relative humidity rates decrease, and overall annual rainfall decreases. For Iraq, this results in an increment in net solar radiation and evapotranspiration rates, so that a lack in water resources is becoming an obvious fact, causing a rapid reduction in Iraq's animal and agricultural resources.

Materials and Methods

In 1980s, the environmental influences of global warming were clear and reached peak values. Using this fact as a start point, this research adopted the aim of quantitatively revealing the fluctuations of these influences on Iraq's annually net solar radiation rates during the last thirty years. To accomplish this purpose, two kinds of data were adopted; The first kind of data was specified meteorological readings from 9 stations, which were selected to have a comprehensive distribution in order to cover all Iraq’s area, for ten year intervals during a temporal range of 1987 to 2017, as illustrated in Figure-2.

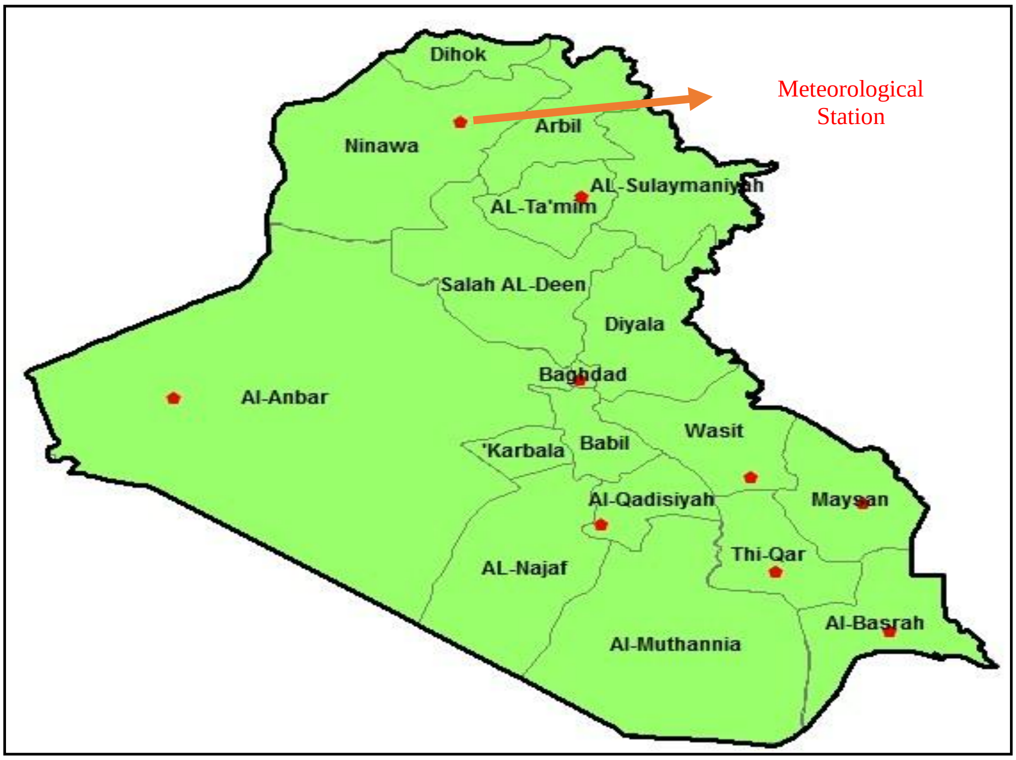

Figure 2- The geographical locations of meteorological stations that ensure comprehensive distribution in Iraq’s area.

The weather readings were composed of monthly mean relative humidity, monthly mean maximum temperature, and monthly mean minimum temperature. The second kind of data was the height (Z) above sea level (m ASL) each station. These data were acquired from ASTER "Global-Digital Elevation Model" satellite image for Iraq with spatial resolution equal to 30 meters for each pixel, as shown in Figure-3.

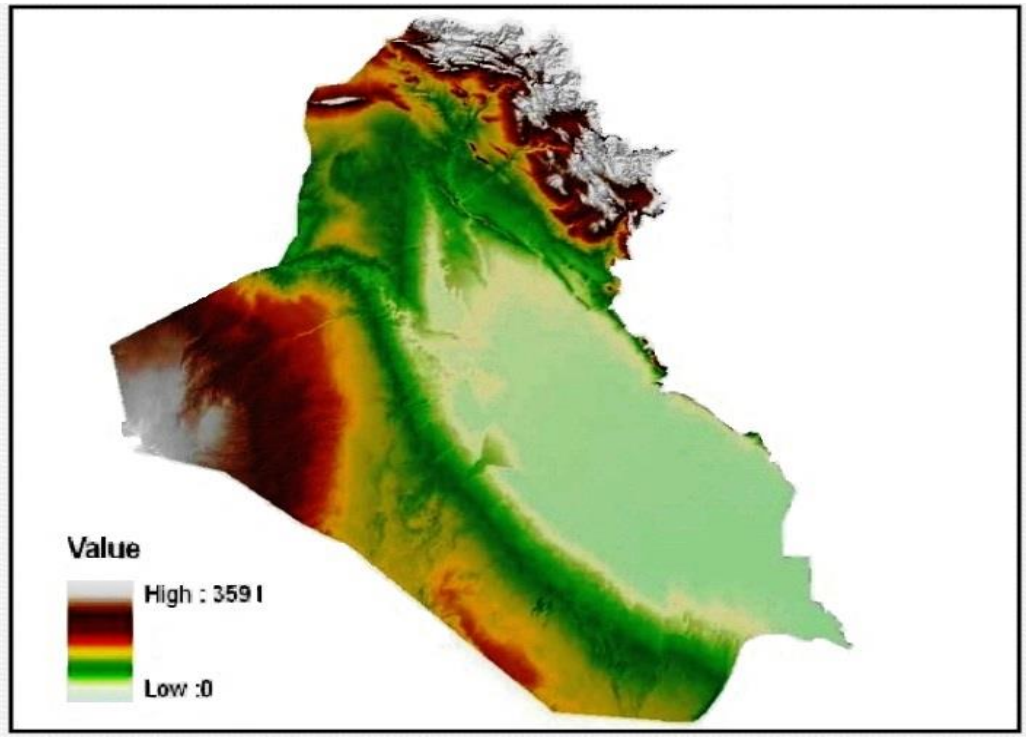

Figure 3- Global Digital Elevation Model of Iraq with 30 m pixel spatial resolution.

The utilized equations for determining net solar radiation are daily measurement equations; each mean monthly meteorological reading was expanded to be daily reading, by adopting a mathematical rule (the mean of a list of values could stand for each value, but the reverse is not true). The remaining information ($\mathbf{R_a}$, $\mathbf{R_s}$, $\mathbf{R_{so}}$, $\mathbf{R_{ns}}$, $\mathbf{R_{nl}}$, **and** $\mathbf{e_a}$) were calculated, where the remotely sensed acquired height (Z) was used to calculate $\mathbf{R_{so}}$.

Table-1 is an illustrative example of daily variables utilized for net solar radiation determination of Baghdad in the first of January, 1987.

Table 1- An example for 1 day variables calculation used to determine net solar radiation in Baghdad (01.01.1987).

d_r	Φ	δ	ω_s	R_a	Z	R_{so}	T_{max}	T_{min}	R_{nl}	R_s
1.0329	0.5791	-0.401	1.289	18.046	31	13.545	18.6	2.6	4.1307	11.549

By using these variables in equation (1), the results of daily $\mathbf{R_n}$. Then, the annual mean $\mathbf{R_n}$ values of each assigned year were calculated, as shown in Table-2

Table2- Annual mean R_n values for the studied meteorological stations (1987, 1997, 2007, and 2017)

Admin.	longitude (Dec. deg.)	latitude (Dec. deg.)	1987's R_n ($MJ.m^{-2}.year^{-1}$)	1997's R_n ($MJ.m^{-2}.year^{-1}$)	2007's R_n ($MJ.m^{-2}.year^{-1}$)	2017's R_n ($MJ.m^{-2}.year^{-1}$)
Baghdad	44.35256	33.273364	10.22	9.932	10	10.117
Basra	47.47	30.31	9.807	9.889	9.816	9.938
Dewaniya	44.57	31.57	9.799	9.875	9.899	10.483
Emara	47.20497	31.810161	9.947	9.869	9.861	9.765
Karkuk	44.36666	35.410581	9.11	9.153	9.545	8.479
Nasiriya	46.31705	31.001656	10	10.021	9.914	10.113
Rutba	40.27356	33.056428	9.827	9.779	9.871	9.974
Hai	46.07636	32.126716	9.643	9.753	9.685	9.617
Mosul	43.15425	36.28746	9.842	9.902	9.503	9.4

The next step was converting each year's R_n annual mean reading into a point shapefile using Arc GIS 10.5 environment. Then, the Inverse Distance Weighting (IDW) spatial interpolation Arc tool was utilized to estimate the annual mean net solar radiation for all Iraq's area , as shown in Figure-4.

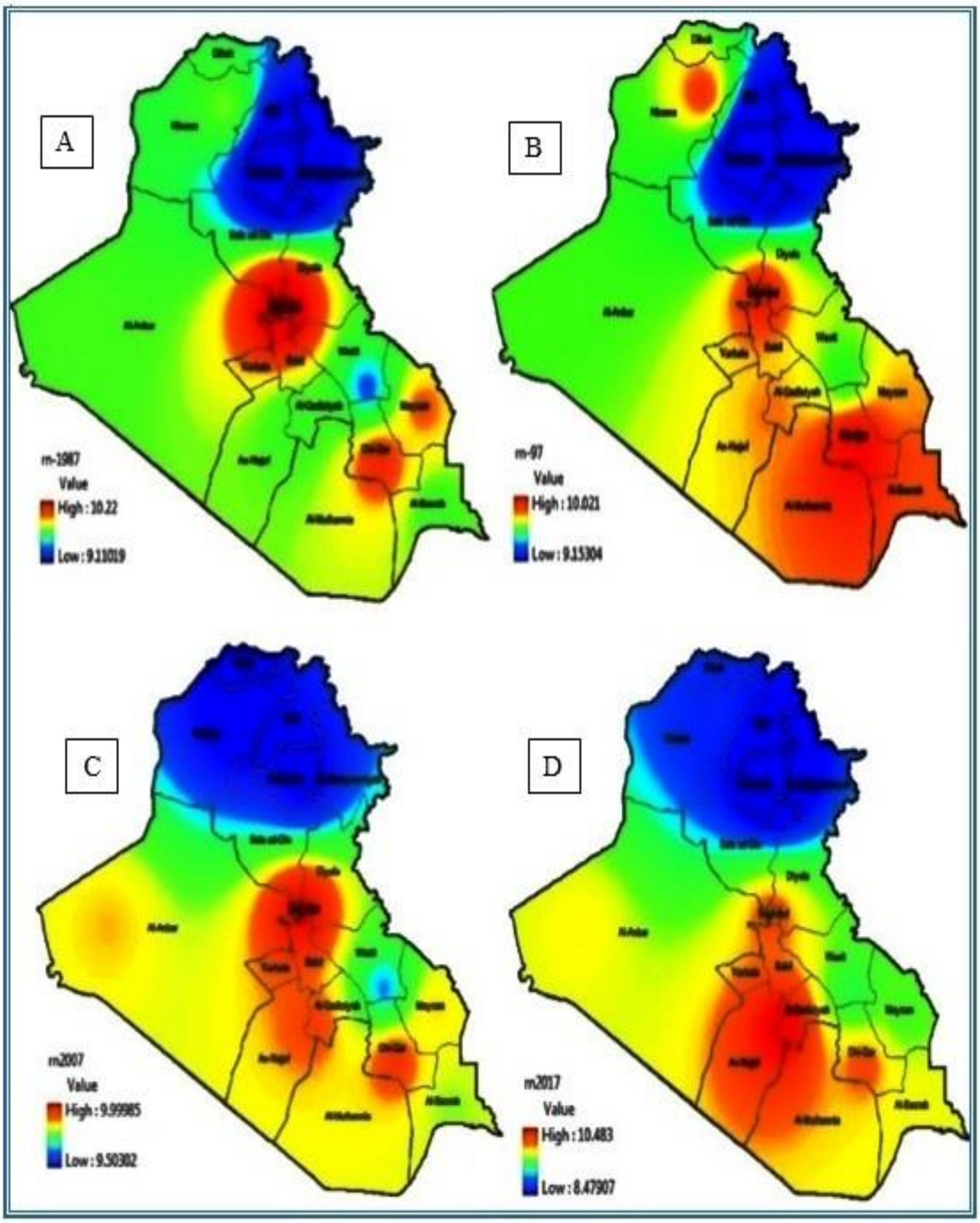

Figure 4- A. The annual mean net solar radiation of Iraq in 1987, B. The annual mean net solar radiation of Iraq in 1997, C. The annual mean net solar radiation of Iraq in 2007, and D. the annual mean net solar radiation of Iraq in 2017.

Results and Discussion

In arid to semi-arid regions such as Iraq, the main climatological factor that affects Rn is relative humidity; effects of clouds, dust, and other particles, as well as topographic features, are considered less important. Iraq's daily climate is a result of two regions of climate interaction; these are the subtropical aridity of the Arabian Desert and the subtropical humidity of the Arabian Gulf. RH annual mean values for Iraq are stated to range between 31 and 50%. Topographic factors in Iraq's northern parts cause relative humidity rates higher than those in the middle and southern parts. The rates of RH annual means and their variations in the studied time-interval due to those two climate interaction are illustrated in Table-3.

Table 3- Annual mean relative humidity rates and their variations for some Iraqi administrative regions (1987)

Administrative area	1987	1997	2007	2017	1997-1987 percentage variation	2007-1987 percentage variation	2017-1987 percentage variation
Baghdad	**41.2**	**47.4**	**39**	**37.8**	**15.04854**	**-5.33981**	**-8.25243**
Basra	**41.7**	**43.4**	**40.3**	**37.4**	**4.076739**	**-3.35731**	**-10.3118**
Dewaniya	**48**	**49.8**	**45**	**45.9**	**3.75**	**-6.25**	**-4.375**
Emara	**47.1**	**46.6**	**46.9**	**38**	**-1.06157**	**-0.42463**	**-19.3206**
karkuk	**43.2**	**50**	**44.3**	**46.8**	**15.74074**	**2.546296**	**8.333333**
Nasiriya	**38.3**	**45.8**	**39.3**	**33.2**	**19.58225**	**2.610966**	**-13.3159**
Rutba	**46.7**	**51.3**	**45**	**43**	**9.850107**	**-3.64026**	**-7.92291**
Hai	**45.8**	**42.7**	**41.9**	**40.4**	**-6.76856**	**-8.51528**	**-11.7904**
Mosul	**50**	**54.8**	**50.5**	**52**	**9.6**	**1**	**4**

in the studied time-interval variations of relative humidity rates restricted (Rn annual means) to change. This is shown in Table-4.

Table 4-Percentage variation of net solar radiation values for some Iraqi administrative regions (1987).

Administrative areas	(1997-1987) percentage variation	(2007-1987) percentage variation	(2017-1987) percentage variation
Dewaniya	**0.81716**	**1.02145**	**7.048008**
Emara	**-0.70423**	**-0.80483**	**-1.81087**
Hai	**1.141079**	**0.414938**	**-0.3112**
Karkuk	**0.439078**	**-6.25686**	**-7.02525**
Mosul	**0.609756**	**-3.45528**	**-4.47154**
Nasiriya	**0.2**	**-0.9**	**1.1**
Baghdad	**-2.83757**	**-2.15264**	**-1.07632**
Basra	**0.816327**	**0.102041**	**1.326531**
Rutba	**-0.50916**	**0.509165**	**1.527495**

As can be quantitatively noticed from Table-4, the 1980s decade had the peak Rn rates all over Iraq. Then, the general behavior of Rn rates was geographically based , i.e. raising in the middle and southern regions and descending in the northern regions). However, to clarify this behavior of the net solar radiation rates since 1987, a standard annual mean Rn rate of Iraq weather was selected as a basis to evaluate the areas with equal or higher values compared to this standard. This selected standard annual mean Rn value was **9.8MJ.m^{-2}.year^{-1}.** This "geographically based phenomenon" is shown in Figure-5.

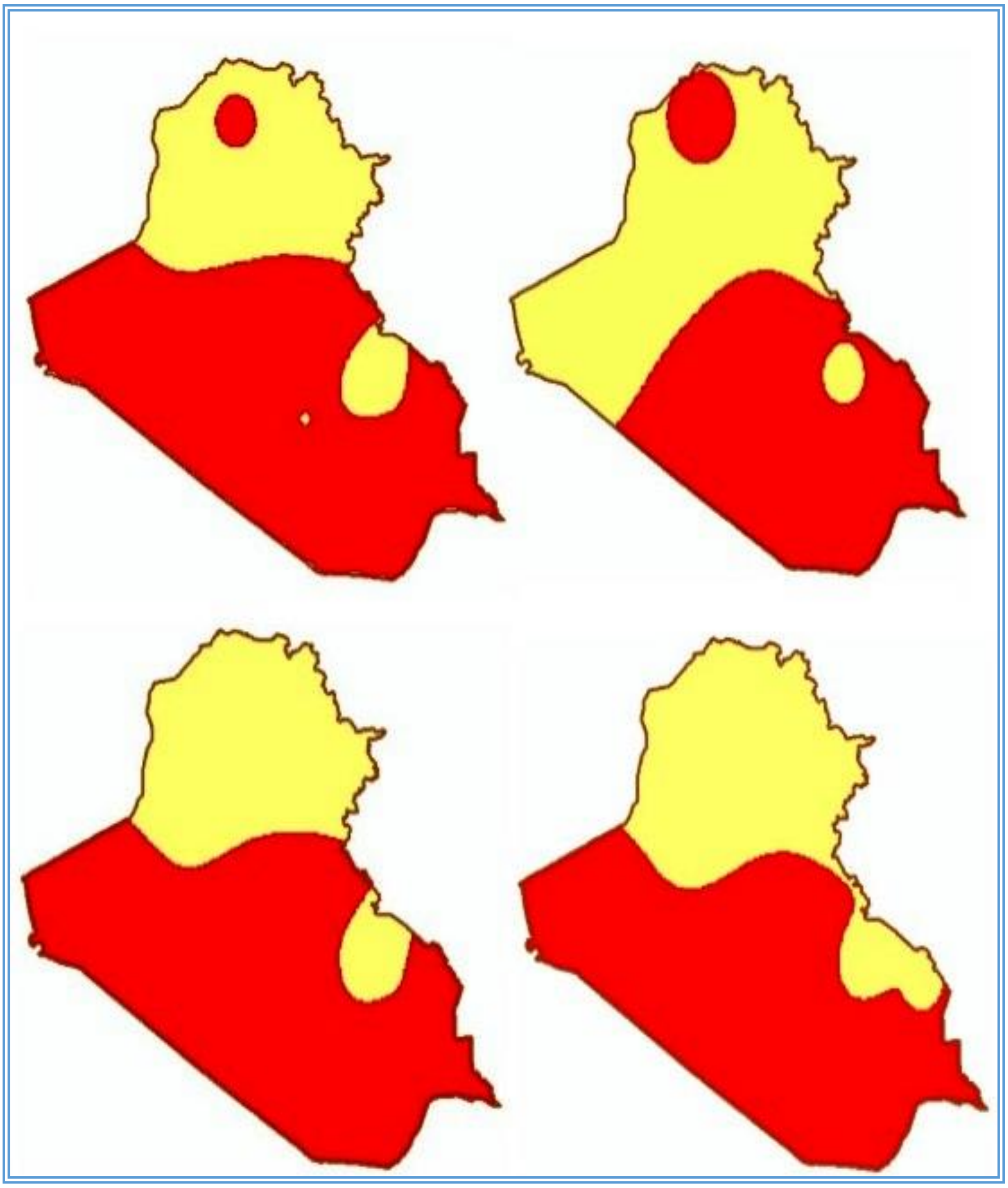

Figure 5- A The regions of Iraq with Rn equal or higher than 9.8 MJ.m^{-2}.year^{-1} (red color) in 1987, B. The regions of Iraq with Rn equal or higher than 9.8 MJ.m^{-2}.year^{-1} (red color) in 1997, C. The regions of Iraq with Rn equal or higher than 9.8 MJ.m^{-2}.year^{-1} (red color) in 2007, and D. The regions of Iraq with Rn equal or higher than 9.8 MJ.m^{-2}.year^{-1} (red color) in 2017.

Figure-5 illustrates that the total area in Iraq with annual mean Rn equal or higher than 9.8 MJ.m^{-2}.year^{-1}was 305088.098 km^2 in 1987, which was reduced to 241984.77 km^2 in 1997, then increased to 294491.136 km^2 in 2007, then decreased again to 277272.542 km^2 by 2017.

Conclusions

- Annual mean values of relative humidity for Iraq ranged 31-50%, which resulted from the interaction of subtropical arid climate of the Arabian Desert and subtropical humid climate of the Arabian Gulf.
- Relative humidity rates in Iraq's northern parts were higher than those in the middle and southern parts, because of the topographic factor effects.

- In Iraq, Rn is majorly influenced by relative humidity, as compared to effects of clouds, dust, and topographic features which are considered less important.
- In this work, it is obvious that the 1980s decade had the peak Rn rates all over Iraq. After that, the general behavior of net solar radiation rates was geographically based, i.e. raising in middle and southern regions and descending in the northern parts of Iraq.

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