EVALUATION AND CALIBRATION OF METHODS ESTIMATING SOLAR RADIATION AND ITS EFFECT ON REFERENCE CROP EVAPOTRANSPIRATION +

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Abstract:

This study aims to evaluate and calibrate the methods of estimation solar radiation and their effect on reference crop evapotranspiration in Mosul area . The climatological data are presented for average 30 years 1971-2000 of Mosul station , which include monthly average maximum and minimum temperatures , mean relative humidity, wind speed , sunshine hours, and measured incoming solar radiation . These data are used to calculate monthly solar radiation by Angstrom and Hargreaves equations and reference evapotranspiration ETo by Penman-Monteith equation. The results of estimated monthly solar radiation are listed , plotted and compared with measured solar radiation . The coefficient of determination (R^2) and the Root Mean Square Error (RMSE) are calculated . The values of R^2 and RMSE are 0.998 and 3.6 MJ m^{-2} day^{-1} for Angstrom method and are 0.996 and 4.2 MJ m^{-2} day^{-1} for Hargreaves method . The results showed that the method of estimate of solar radiation by the Angstrom formula gave the highest R^2 and smallest RMSE and , therefore it is the best way to calculate the solar radiation . But in case of absence measured solar radiation in calculation ETo led to overestimated by 9% for Angstrom and 11% for Hargreaves . The two linear regression equations are used to calibrate the coefficients of Angstrom and Hargreaves methods to Mosul area . The average ETo was 3.39 mm day^{-1} for measured solar radiation .

تقييم ومعايرة طرائق حساب الإشعاع الشمسي وأثره على التبخر-نتح المرجعي

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المستخلص:

تهدف هذه الدراسة لتقيم ومعايرة طرائق تخمين الإشعاع الشمسي وإثره على حساب التبخر–نتح المرجعي في منطقة الموصل . وقدمت فيها بيانات مناخية تمثل المعدل الشهري لمحطة الموصل لـ30 عام من 1971 لغاية 2000 والتي تتضمن درجة الحرارة العظمى والصغرى، الرطوبة النسبية ، سرعة الرياح ، فترة سطوع الشمس، والإشعاع الشمسي الوارد المقاس . تم استخدام تلك البيانات في حساب الإشعاع الشمسي الوارد بطريقتي انكستروم وهاركفيس والتبخر – نتح المرجعي باستخدام معادلة بنمان – مونتيث . تم إدراج النتائج في جداول ورسمها في إشكال توضحيه ومقارنتها مع الاشعاع الشمسي المقاس . تم حساب معامل التحديد R^2 وجذر متوسط مربع الخطأ RMSE ، حيث كانت 0.998 و3.6 ميكاجول.م$^{-2}$.يوم$^{-1}$ لمعادلة انكستروم وكانت 0.996 و4.2 ميكاجول.م$^{-2}$.يوم$^{-1}$ لمعادلة هاركفيس

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. وأظهرت هذه النتائج بان معادلة انكستروم تعطي أعلى معامل تحديد واقل قيمة لجذر متوسط مربع الخطأ وذلك تعتبر أفضل طريقة لحساب الاشعاع الشمسي . ولكن في حالة حساب التبخر-نتح ETo فانه تعطي نتائج مبالغ به للتبخر- نتح بمقدار 9% باستخدام طريقة انكستروم و11% باستخدام طريقة هاركفيس عن التبخر-نتح باستخدام الإشعاع الشمسي المقاس . تم استخدام معادلتين الانحدار الخطي لمعايرة معاملات طريقتي انكستروم وهاركفيس لمناخ مدينة الموصل . ان معدل التبخر-نتح اليومي خلال فترة الدراسة كان 3.39 ملم يوم$^{-1}$ بواسطة الاشعاع الشمسي المقاس .

Introduction:

The radiation striking a surface perpendicular to the sun's rays at the top of the earth's atmosphere, called the solar constant, is about 0.082 MJ m^{-2} min^{-1}. The local intensity of radiation is, however, determined by the angle between the direction of the sun's rays and the normal to the surface of the atmosphere .This angle will change during the day and will be different at different latitudes and in different seasons .The solar radiation received at the top of the earth's atmosphere on a horizontal surface is called the extraterrestrial radiation, Ra [1] . Part of Ra is absorbed and scattered when passing through the atmosphere . The remainder , including some that is scattered but reaches the earth's surface , is identified as solar radiation Rs [2] .

The solar radiation Rs is a primary driver of evapotranspiration ET process and Rs data are an integral part of many ET estimation procedures [3].

The reference evapotranspiration (ETo) in the FAO Penman-Monteith method , is defined as the rate of evapotranspiration from a hypothetic crop with an assumed crop height (12 cm) and a fixed canopy resistance (70) [s m^{-1}], and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water [4].

The meteorological station records often consist only of precipitation and air temperature data. There is therefore a need for appropriate methods to estimate solar radiation data to enable complete data set creation, by combining observed and estimated data [5].

There are various methods to estimate solar radiation if the solar radiation is not measured include [1] :1-From Angstrom formula , 2-From a nearby weather station , 3-From air temperature differences , 4-From empirical methodology for island locations .

Many studies have been estimated solar radiation with minimum data using only temperature data , then it uses in to estimate the ETo such as authors in [6 ,7 ,8 ,9] .

A site-specific model was developed by [10] to predict radiation Rs using a multiple-regression equation. They used data set to generate the model contained daily Rs, Tmax, Tmin, and precipitation for the years of 1997 and 1998 to Keiser in north of America .

A computer software was developed by [11] to facilitate the calculation of daily FAO Penman-Monteith reference crop evapotranspiration and to estimate errors that can arise if solar radiation ,wind speed ,vapor pressure data are not available .

The procedure was considered by [12] to estimate the missing radiation data using the maximum and the minimum daily temperature differences for study carried out in South Bulgaria.

The authors in reference [13] calibrated the empirical radiation estimation in FAO Penman–Monteith model by observed solar radiation of 81 meteorological stations over China during 1971–2000, and measurements of net longwave radiation in the Tibetan Plateau , and they recommended that Angstrom formula for estimating solar radiation based on simple annual linear regression and ETo was overestimated of 27% if no local calibration in China .

The author in reference [3] introduced a relatively simple procedure for self-calibrating and applying an air-temperature-based equation for predicting daily and monthly solar radiation .The procedure uses clear-sky solar radiation envelopes and daily maximum and minimum air temperature . He tested method at nine locations in United State and was generally accurate , especially when predicting monthly Rs .

The authors in reference [14] calculated evapotranspiration in central Iraq from Penman method and three of its modifications , grass lysimeter and field experiments of four crops and they proposed coefficients for Angstrom formula were 0.383 and 0.428 with Rs/Ra to n/N .

The aim of the study is to evaluate and calibrate methods of estimation incoming solar radiation and its effect on reference crop evapotranspiration in the Mosul area . The climatic data used represents the monthly average of Mosul station for 30 years 1971–2000 . The Mosul station is located in the city of Mosul in North of Iraq at latitude 36º 19' and 223 m above sea level .

Materials and Methods :

Methods of estimation incoming solar radiation Rs :

1. From Angstrom formula :

The authors in reference [1] describe the Angstrom as :

$$Rs = \left(a_s + b_s \frac{n}{N} \right) Ra \qquad \text{----------------(1)}$$

where

Rs : solar or shortwave radiation (MJ m^{-2} day^{-1}), n : actual duration of sunshine (hour) , N : maximum possible duration of sunshine or daylight hours (hour) , Ra : extraterrestrial radiation (MJ m^{-2} day^{-1}), a_s : regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0) , $a_s + b_s$ fraction of extraterrestrial radiation reaching the earth on clear days (n = N) .

The values a_s = 0.25 and b_s= 0.50 were recommended from [1] where no actual Rs data are available and no calibration has been carried out . In this study the values a_s = 0.25 and b_s= 0.50 are used in Angstrom formula .

The extraterrestrial radiation, Ra , can be estimate from the following equation in reference [1]:

$$Ra = \frac{24*(60)}{\pi} * G_{sc} * dr[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \qquad \text{-------------(2)}$$

where

Ra : extraterrestrial radiation MJ m^{-2} day^{-1} , G_{sc} : solar constant = 0.082 MJ m^{-2} min^{-1}, dr : inverse relative distance Earth-Sun , ω_S : sunset hour angle in radians , δ : solar declination in radians , φ : latitude in radians . The standardized equations for computing all parameters (dr , ω_S , δ) are given in reference [1]. In this study the φ is 0.63 in radians for Mosul station.

2. From the Hargreaves formula :

The authors in reference [15] describe the Hargreaves formula as :

$$Rs = K_{Rs}\sqrt{(T_{max} - T_{min})}Ra \qquad \text{----------------------(3)}$$

where :

T_{max} :maximum air temperature [°C] , T_{min} : minimum air temperature [°C] , k_{Rs} : calibration coefficient . The authors in [1] were adopted the k_{Rs} for 'interior' locations$\cong$ 0.16 and 'coastal' locations ≅ 0.19 . In this study the k_{Rs} is 0.16 . The Hargreaves formula performs best using mean monthly data ,when applied to daily data , it trends to overestimate for cloudy days . Rs predicted by equation (3) should be limited to ≤ clear-sky radiation R_{so} [16] .

The R_{so} is the solar radiation that would reach the same surface during the same period but under cloudless conditions [1] . The calculation of the clear-sky radiation R_{so} , when n=N , can be estimate from the following equation in reference [1]:

$$R_{so} = \left(0.75 + 2*10^{-5} Z\right) Ra \qquad \text{-------------------(4)}$$

where :

Z :station elevation above sea level [m]. In this study the Z equals 223m for Mosul station .

<u>Reference crop evapotranspiration ETo :</u>

The reference crop evapotranspiration ETo was calculated using FAO Penman-Monteith equation according to the procedure proposed by references [1,16,17,18]. For calculation monthly ETo requires monthly average measured solar radiation Rs , minimum T_{min} , maximum temperature T_{max} , air humidity RH , wind speed U_2 , and sunshine n if absence measured solar radiation data. The FAO Penman-Monteith (mm day $^{-1}$) was described in reference [1] as :

$$ET_0 = \frac{0.408\ \Delta(R_n - G) + \gamma \dfrac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)} \qquad \text{------------------(5)}$$

Where:

R_n : net radiation at the crop surface [MJ m^{-2} day^{-1}],
G : soil heat flux density [MJ m^{-2} day^{-1}] ,
T : average air temperature at 2 m height [°C] ,
U_2 : wind speed at 2 m height [m s^{-1}] ,
e_s : saturation vapor pressure [kPa] ,
e_a : actual vapor pressure [kPa] ,
es-ea : saturation vapor pressure deficit [kPa] ,
Δ : slope vapor pressure curve [kPa °C^{-1}] ,
γ : psychrometric constant [kPa °C^{-1}] .

The average climate data 1971-2000 to Mosul station which obtained from the Iraqi meteorological office in reference [19] and the reference crop evapotranspiration ETo by Penman-Monteith , are listed in the Table (1) .

Table (1) shows average climate data and the ETo by Penman-Monteith for period 1971-2000 to Mosul station

Months	T_{max}	T_{min}	T_{avg}	RH	U_2 at 2 m	n	Rs measured	ETo

	(°C)	(°C)	(°C)	(%)	(m s^{-1})	(hours)	MJ m^{-2} day^{-1}	mm day^{-1}
Jan	12.4	2.3	7.35	79.8	0.69	4.8	7.2	0.89
Feb	14.7	3.3	9.0	73.7	0.99	5.9	10.1	1.41
Mar	18.8	6.5	12.65	68.0	1.01	6.7	13.2	2.15
Apr	25.0	10.9	18.0	61.6	1.12	8.0	16.7	3.28
May	32.7	16.0	24.35	43.5	1.30	10.2	19.9	4.88
Jun	39.1	21.2	30.15	27.6	1.32	12.0	22.7	6.23
Jul	42.7	24.9	33.8	24.3	1.33	12.2	22.0	6.56
Aug	42.4	23.9	33.15	26.3	1.11	11.7	20.3	5.75
Sep	38.2	18.8	28.5	30.8	0.81	10.5	17.5	4.37
Oct	30.5	13.1	21.8	45.9	0.62	8.4	12.6	2.72
Nov	21.0	7.2	14.1	66.1	0.53	6.4	8.6	1.5
Dec	13.9	3.7	8.8	80.1	0.62	4.5	6.5	0.93
average	27.6	12.6	20.1	52.3	0.95	8.4	14.8	3.39

T_{avg} =(T_{max} + T_{min})/2 ,
U_2 at 2m= U_2 at 10m *0.75 from reference [1] ,
Rs measured (computed as average in 24-hours in unit MJ m^{-2} day^{-1}) ,
ETo by Penman-Monteith based on the measured solar radiation .

Results of solar radiation :

The results of estimation the solar radiation (the extraterrestrial radiation , the clear-sky radiation , the Hargreaves , the Angstrom and the measured solar radiation)MJ m^{-2} day^{-1} for average data 1971-2000 to Mosul station , are listed in the Table (2) and plotted in the Fig (1) .

Table (2) shows the results of estimation monthly radiation MJ m^{-2} day^{-1} for average data 1971-2000

Months	Ra MJ m^{-2} day^{-1}	Rso MJ m^{-2} day^{-1}	Rs-Hargreaves MJ m^{-2} day^{-1}	Rs-Angstrom MJ m^{-2} day^{-1}	Rs measured MJ m^{-2} day^{-1}
Jan	17.3	13.1	8.8	8.6	7.2
Feb	22.6	17.1	12.2	11.9	10.1
Mar	29.7	22.4	16.7	15.8	13.2
Apr	36.0	27.2	21.6	20.2	16.7
May	40.2	30.3	26.3	24.7	19.9
Jun	41.7	31.5	28.2	27.8	22.7
Jul	40.5	30.6	27.4	27.6	22.0
Aug	36.9	27.8	25.4	25.5	20.3
Sep	31.0	23.4	21.8	21.2	17.5
Oct	24.1	18.2	16.1	15.3	12.6
Nov	18.4	13.9	10.9	10.5	8.6
Dec	16	12.1	8.2	7.8	6.5
average	29.5	22.3	18.6	18.1	14.8

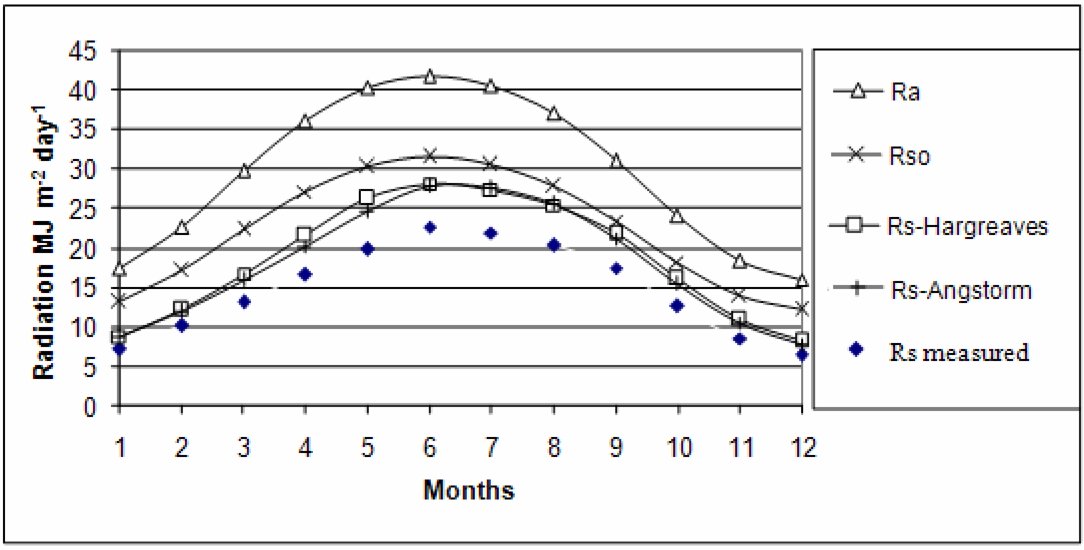

Fig (1) the results of estimation monthly radiation MJ m^{-2} day^{-1} for average data 1971-2000

It appears from the Table (2) , the annual average of Ra is 29.5 MJ m^{-2} day^{-1}, the R_{so} is 22.3 MJ m^{-2} day^{-1} , the Rs by Hargreaves is 18.6 MJ m^{-2} day^{-1}, the Rs by Angstrom is 18.1 MJ m^{-2} day^{-1} , the Rs measured is 14.8 MJ m^{-2} day^{-1} . There is little difference between the estimated solar radiation ways Angstrom and Hargreaves , while increasing the difference between the measured and estimated due to the lack of calibration of these equations in the Mosul city .

The extraterrestrial radiation Ra is a maximal while the solar radiation Rs is a minimal because the radiation when it passes in to atmosphere distract part of it . The authors in [1] reported that for a cloudless day , Rs is roughly 75% of extraterrestrial radiation .On a cloudy day , the radiation is scattered in the atmosphere , but even with extremely dense cloud cover , about 25% of extraterrestrial radiation may still reach the earth's surface mainly as diffuse sky radiation .

The authors in [20] also reported that the main resources in solar radiation loss were the clouds and the dust particles in different regions in Iraq and mean annual values of solar radiation loss had recorded as 22% in Mosul city .

From the Fig (1) , the incoming solar radiation , Rs, varying from month to month . It is low in winter and then increasing in the spring until it reaches its highest value in June . It falls gradually also to reach the lowest value in the month of December due to decrease in sunshine hours and increase in number of cloudy days in winter season .

The clear-sky radiation , R_{so} , is higher than incoming solar radiation in all months because the cloudiness and the interval of dust occur in days of year , however the loss in solar radiation in summer and autumn season is less than in winter and spring seasons .

Evaluation the methods of estimation solar radiation :

The criteria evaluation such as the coefficient of determination (R^2) and the Root Mean Square Error (RMSE) , are applied to evaluate methods of estimation incoming solar radiation with measured solar radiation . The R^2 can be estimate from the following equation in reference [21] :

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(m - \bar{m} \right)\left(e - \bar{e} \right)}{\sqrt{\sum_{i=1}^{n} \left(m - \bar{m} \right)^2 \sum_{i=1}^{n} \left(e - \bar{e} \right)^2}} \right]^2 \qquad \text{-------------------(6)}$$

The RMSE can be estimate from the following equation in reference [22] :

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (m-e)^2}{n}} \qquad \text{-------------------(7)}$$

Where:

e : estimated solar radiation [MJ m^{-2} day^{-1}] , $\bar{e}$: average of the estimated solar radiation [MJ m^{-2} day^{-1}] , m : measured solar radiation [MJ m^{-2} day^{-1}] , $\bar{m}$: average of the measured solar radiation [MJ m^{-2} day^{-1}] , n : number of data .
The results of R^2 and RMSE are listed in the Table (3) . The best methods for estimated solar radiation is the Angstrom because it gave the highest R^2 and smallest RMSE .

Table (3) shows the results of R^2 and RMSE to evaluation methods of estimation incoming solar radiation

Methods	Angstrom	Hargreaves	Clear sky	Ra
R^2	0.998	0.996	0.960	0.959
RMSE MJ m^{-2} day^{-1}	3.6	4.2	7.7	15.2

Calibration of solar radiation :

The calibration carried out on two liner regression equations for the Angstrom ($Y=a_s+b_s x$) and Hargreaves ($Y=k_{Rs} x$) equations in MATLAB program . Where , the Y is the ratio of the Rs to the Ra (Rs/Ra) in both two liner regression , a_s : the Y-intercept (i.e., the value of Y when x= 0) , b_s : the slope of relation between Rs/Ra and n/N , x : the ratio of n to N (n/N) in the Angstrom or the values of $(T_{max}-T_{min})^{0.5}$ in the Hargreaves , K_{Rs} : the slope of relation between Rs/Ra and $(T_{max}-T_{min})^{0.5}$. The results of calibration are listed in the Table(4) , and plotted in the Fig (2) .

Table (4) shows the results of calibration (coefficients a_s and b_s and K_{Rs}) .

	Angstrom equation			Hargreaves equation		
Average years	a_s	b_s	R^2	K_{Rs}	R^2	n
1971-2000	0.25	0.35	0.98	0.127	0.94	12

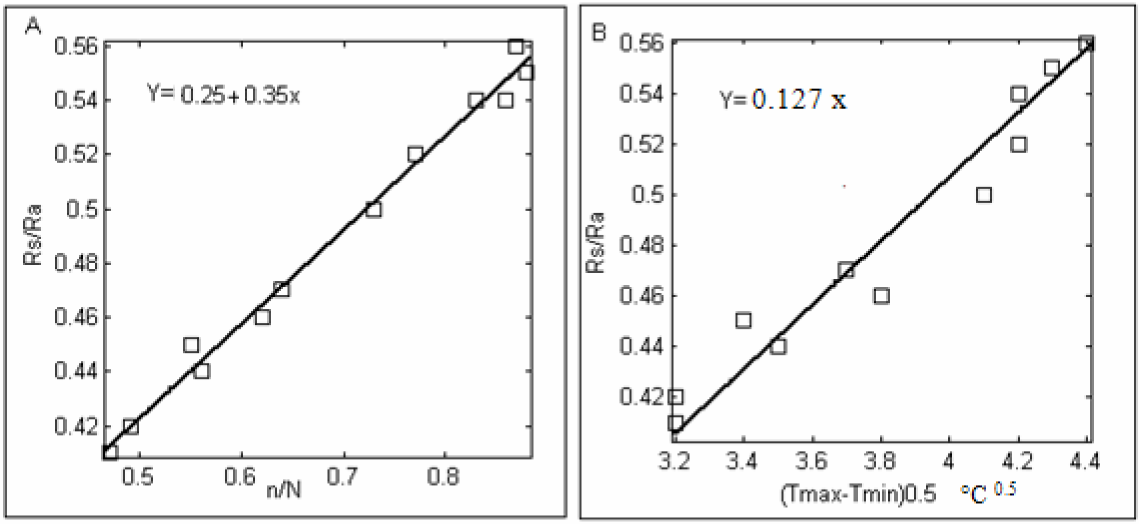

Fig (2) the relationships of solar radiation , A between Rs/Ra and n/N , and B between Rs/Ra and $(Tmax-Tmin)^{0.5}$ for average data 1971-2000

Results of reference evapotranspiration (ETo) :

The results of reference evapotranspiration ETo by Penman-Monteith equation based on measured and estimated solar radiation (Angstrom and Hargreaves) , are plotted in the Fig (3) . It appears from the Fig(3) , that the ETo from solar radiation of Hargreaves is the highest because that the ETo calculations depend on measured solar radiation and when using estimating solar radiation by Hargreaves , the ETo increases with increasing solar radiation .

The annual average ETo was 3.39 $mm.day^{-1}$ from measured solar radiation , 3.76 $mm.day^{-1}$ from solar radiation of Hargreaves , 3.71 $mm.day^{-1}$ from Angstrom . The ETo based on the estimated solar radiation from Hargreaves and Angstrom were overestimated by 11 % and 9 % respectively if no local calibration.

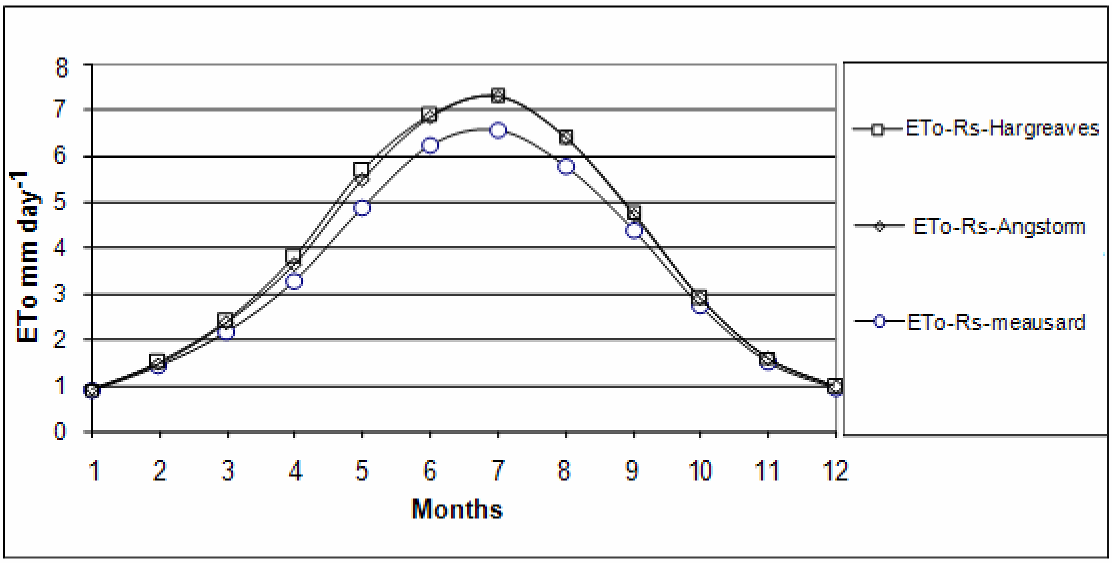

Fig (3) the reference evapotranspiration ETo by Penman-Monteith based on measured and estimated solar radiation from Hargreaves and Angstrom for average data 1971-2000

Conclusions :

The methods of estimation solar radiation are tested at Mosul station for monthly average study years 1971-2000 by the correlation coefficient R^2 and the root mean square error RMSE . The results show the method of estimating solar radiation from the Angstrom gave highest R^2 and smallest RMSE . But , it used in calculation ETo to Mosul area led to overestimation in ETo by 9% for Angstrom and 11% for Hargreaves if no local calibration . Therefore uses adjusted coefficients 0.25 and 0.35 in Angstrom equation based on Rs/Ra to n/N for monthly data with R^2 equals 0.98 and K_{Rs}=0.127 in Hargreaves equation based on Rs/Ra to $(T_{max}-T_{min})^{0.5}$ with R^2 equals 0.94 .

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