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Evaluation of an Improved Empirical Equation for Estimation of Reference Evapotranspiration in Arid Areas

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ABSTRACT

A model for predicting the reference evapotranspiration ET_o in arid areas was developed and evaluated. The model was developed based on the Jensen-Heise model with added coefficients and the original coefficients of the model were calibrated for the conditions of the area. For evaluation, the ET_o values of the model were compared to the ET_o values obtained using the *FAO* Penman Monteith method. The model was also evaluated using a set of weather data (14 years of data) obtained from a location 350 km from the original site. The model improved the prediction at the original site reducing the overall Mean Absolute error (*MAE*) from 1.62 using the Jensen-Heise model to 0.84 using the Modified Jensen-Heise (*MJH*) model. Calibrating the values of the coefficients to the new location improved the performance of the model and made it better than the Jensen-Heise model decreasing the overall *MAE* from 2.75 for the Jensen-Heise model to 1.24 and 1.22 for the 3 and the 14 years calibration, respectively.

Keywords: Reference evapotranspiration, Modeling, Arid.

INTRODUCTION

The limitation of water recourses and dry climate in arid areas are the major issues faced in agriculture around the world. The water requirements of a plant depend mainly on the predicted reference evapotranspiration (ETo), which gives the management of irrigation systems high efficiency. Many models used to estimate reference evapotranspiration (ETo) such as those of (Blaney-Criddle ,1950), and (Hargreaves and Samani ,1985) are classified as temperature based while that of (Jensen and Haise ,1963) is classified as radiation based. Although there are several methods for the estimation of reference evapotranspiration (ETo), the Penman-Monteith equation (Allen et al., 1998) remains the most used around the world and recommended by many researchers (Jensen et al., 1990; Yoder et al., 2005; Mcmahon et al., 2012). But the Penman-Monteith equation requires data which are not available everywhere, for this reason the works of many researchers were evaluated with many simple methods in different parts of the world. The radiation based methods under arid and semi-arid conditions were poor (Er-Raki et al., 2010) or too high when compared with the Penman-Monteith equation (Xu and Singh, 2002). In Hungary, temperature based models such as the Blaney-Criddle model was close to the Penman-Monteith equation (Racz et al., 2013) but in Saudi Arabia the value of the Blaney-Criddle model was lower by 26.8% compared to the Penman-Monteith equation (Alharbi et al., 2016). This error increased for the Blaney-Criddle value compared to the Penman-Monteith equation in summer than in winter (Alhabi and Alzoheiry, 2018). Zarei et al. (2015) reported that radiation-based methods such as the Jensen-Haise and Thornthwaite equations compared to the Penman-Monteith method were significantly different. But the Jensen-Heise equation recorded the closest estimation to the Penman-Monteith method. In addition, the values of reference evapotranspiration (ETo) used by Hargreaves and Samani and Thornthwaite equations were overestimated compared to the Penman-Monteith method (Alhabi and Alzoheiry, 2018). The aim of this study was to develop and evaluate an equation to improve the accuracy of the predictions of the ETo with minimum requirements of metrological data and evaluate the possibility of using this equation in any other arid location.

MATERIALS AND METHODS

1.Determination of reference evapotranspiration (*ETo*)

The most accurate method used for reference evapotranspiration (ETo) prediction is the FAO Penman-Monteith method, but the data required for the equation is not always available specially when historical records are needed for statistical analysis. Alharbi and Alzoheiry, (2018) found the Jensen-Heise model, to be the closest in its results to the FAO equation in hot arid areas. In order to increase the accuracy of its' prediction a modification of the Jensen-Heise model was used to predict the reference evapotranspiration values, and the values of the original and modified models were compared to the values obtained the FAO Penman-Monteith method. Data sets for the developing the model were obtained from an agricultural weather station in Burydah, KSA (26°19'35.6"N 43°46'13.2"E).

Jensen-Heise model (*JH*)

The Jensen-Heise model is an empirical equation based on energy balance and was reported by Hansen et al. (1980) as:

$$ET_{\circ} = C_T.(T - T_x).K_T.R_a.T.D^{0.5} \quad (1)$$

Where:

ET_o is the daily reference evapotranspiration (mm/day);
C_T, T_x and K_T are standard coefficients;
R_a is the extra-terrestrial radiation ($MJm^{-2}day^{-1}$);
T is the average daily temperature (°C); and
D is the difference between maximum and minimum daily temperatures (°C).

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Penman-Monteith-*FAO*-56 model (*PM*):

The *FAO* Penman-Monteith Method *(PM)* has a strong theoretical basis for calculating *ETo* and can be written as:

$$ET_{\circ} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 034 u_2)} \quad (2)$$

Where:

***ETo* is the reference evapotranspiration (mm day^{-1});**
R_n is the net radiation (MJm^{-2}day^{-1});
***G* is the soil heat flux density (MJm^{-2}day^{-1});**
Δ is the slope vapor pressure (kPa°C^{-1});
T_a is the mean daily air temperature at 2 m height (°C);
u_2 is the wind speed at 2 m height (ms^{-1});
γ is the psychometric constant (kPa°C^{-1});
e_s is the saturation vapor pressure. (kPa); and
e_a is the actual vapor pressure (kPa).

Modified Jensen-Heise model (*MJH*)

The data of the weather station were collected from a station in Burydah, KSA for three consecutive years. The data set included the maximum and minimum air temperature, maximum and minimum relative humidity, wind speed, and solar radiation. A step backward regression analysis was conducted to include the most effective factors that affect the prediction of the evapotranspiration. The most significant factors were the solar radiation and the temperature while the relative humidity and the wind speed were less significant. Based on that, a modification using the Jensen-Heise model as base model was proposed in equation (3).

The new proposed model (*MJH*) had the form:

$$ET_o = aT_{mean} + bR_a + c(T_{max} - T_{min})^{0.5} \quad (3)$$

Where:

ET_o is the daily reference evapotranspiration (mm/day);
T_{mean} is the mean daily temperature (°C);
T_{max} is the maximum daily temperature (°C);
T_{min} is the minimum daily temperature (°C);
R_a is the solar radiation (MJm^{-2}day^{-1}); and
***a*, *b*, and *c* are constants that can be calibrated for each local area.**

The constants in the equation were determined using the least square method.

2.Evaluating criterion

Mean absolute error (*MAE)*

The *MAE* value for the predicted values were calculated as follows:

$$MAE = \left(\frac{\left(\sum_{i=1}^{i=N} |O_i - E_i|\right)}{N}\right) \quad (4)$$

Where:

O_i is *ETo* from Penman-Monteith and
E_i is the *ETo* from another method for any given day*i*;
***N* is the total number of days (*Willmott and Matsuura, 2005*).**

3.Testing of the modified model in other location

The other data set was for Riyadh (350 Km south of the original site) where 14 years of consecutive data were available. To evaluate if the new model (*MJH*) can be used in other locations with similar weather conditions, the *MJH* model was used to predict the values of reference evapotranspiration in Riyadh, and compared to the values obtained by the *FAO* Penman-Monteith method for the same location. For referencing, the evapotranspiration values were also calculated using the Jensen-Heise (*JH*) equation.

The regression constants were predicted between the evapotranspiration values using the *FAO* method and the corresponding values using the *MJH* or *JH* equation, and T test in pairs.

The predicted evapotranspiration values were plotted against the corresponding values predicted by the *FAO* equation. The proposed equation was then used in Riyadh and the accuracy of the prediction was evaluated using the same methods above.

RESULTS AND DISCUSSION

1.Comparison between the *JH* model and *MJH* model in Buraydah

The values of *a*, *b*, and *c* of equation (3) for Buraydah were 0.118409, 0.204376, and -0.52364, respectively.

The reference evapotranspiration (*ETo*) values were predicted using the Modified Jensen-Heise *(MJH)* model, Jensen-Heise (*JH*) model, and the *FAO* Penman-Monteith for the same years. The mean absolute error *(MAE)* values for the equations are shown in Table (1).

Table 1. The values of the seasonal *MAE* and the overall *MAE* for Buraydah

Season	ET_O from *MJH*, mm day^{-1}	ET_O from *JH*, mm day^{-1}
Winter	0.65	1.74
Spring	1.00	1.59
Summer	1.10	1.46
Autumn	0.64	1.71
Overall	0.84	1.62

The value of the overall (yearly) *MAE* decreased from about 1.62 using the Jensen-Heise model to about 0.84 mm day^{-1} using the *MJH* model. The same trend was found for all seasonal *MAE*. With the use of the *MJH* equation, maximum reduction was achieved in winter when the value of the *MAE* decreased from about 1.74 mm day^{-1}to about 0.65 mm day^{-1}.

The ET_o values for a typical year predicted using the three equations showed that the *MJH* equation is closer in its prediction to the ET_o values predicted by the *FAO* equation. However, it is still not very successful in predicting the extremely high values that occur in some days.

The correlation between the values of ET_o from *FAO* and ET_o from *JH* are shown in Figure (1). The slope of the regression line between the values was 0.935 with an R^2 value of 0.77. The slope value indicates some under estimation of the ET_o values. The correlation between the values of ET_o from *FAO* and ET_o from *MJH* are shown in Figure (2), the slope of the regression line between the values was 0.82 with an R^2 value of 0.84. The slope values indicate an under estimation of the ET_o, but the correlation between the values of the *MJH* equation and the *FAO* equation are stronger than with the *JH* equation.

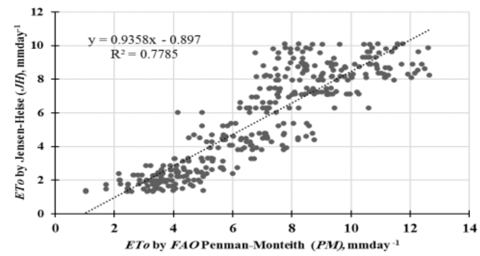

Figure 1. Regression between the values of ET_o from *FAO* and ET_o from *JH*.

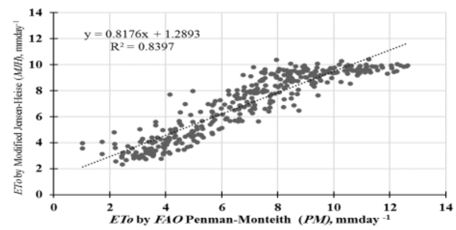

Figure 2. Regression between the values of ET_o from *FAO* and ET_o from *MJH*.

Table (2) presents the T test values between ET_o from *MJH* and ET_o from *FAO*. The values of the T test indicate that the values of the ET_o from *MJH* and ET_o from *FAO* are the same with mean values of 6.968 and 6.946 for ET_o from *MJH* and ET_o from *FAO*, respectively; and a probability value (P) of 0.35.

Table 2. T test between ET_o from *MJH* and ET_o from *FAO*

	Variable 1	Variable 2
Mean	6.945699	6.967896
Variance	7.201747	5.73283
Pearson Correlation	0.916345	
Hypothesized Mean Difference	0	
Df	364	
t Stat	-0.39397	
P(T<=t) one-tail	0.346917	
t Critical one-tail	2.336636	
P(T<=t) two-tail	0.693834	
t Critical two-tail	2.589403	

The T test values between ET_o from *JH* and ET_o from *FAO* are shown in Table (3). The values of the T test indicate that the values of ET_o from *JH* and ET_o from *FAO* are significantly different with mean values of 5.60 and 6.946 for ET_o from *MJH* and ET_o from *FAO*, respectively and a probability value (P) of less than 0.01.

Table 3. *T* test between ET_o from *JH* and ET_o from *FAO*

	Variable 1	Variable 2
Mean	6.967896	5.602509
Variance	5.73283	8.100631
Observations	365	365
Pearson Correlation	0.957732	
Hypothesized Mean Difference	0	
Df	364	
t Stat	29.53178	
P(T<=t) one-tail	5.8E-99	
t Critical one-tail	2.336636	
P(T<=t) two-tail	1.15E-98	
t Critical two-tail	2.589403	

2.Comparison between the original (*JH*) and modified model (*MJH*) in Riyadh

Table (4) shows the *MEA* of the ET_o from *MJH* and ET_o from *JH* in the Riyadh station. The value of the overall (yearly) *MAE* increased from about 2.75 mm day^{-1} using the *JH* to about 3.20 mm day^{-1} using the *MJH* equation. The seasonal *MAE* had the same trend as the values increased for all seasons with the use of the *MJH* equation except for summer, during which the value decreased from 4.21 mm day^{-1} to 3.61 mm day^{-1}. The proposed model was calibrated to fit the local climate conditions in the new location in two different ways, the first calibration used 3 randomly selected years *MJH3* and the second used 14 available years for the calibration of *MJH14*. The values of the year and the seasonal *MAE* were calculated for both calibrations (Table 4). The values of the constants of the original proposed model and for both the calibration in the new location are shown in Table (5).

Table 4. Values of the overall *MAE* and the seasonal *MAE* for Riyadh

Season	*MJH*, mm day^{-1}	*JH*, mm day^{-1}	*MJH3*, mm day^{-1}	*MJH14*, mm day^{-1}
winter	1.77	1.00	1.19	1.14
spring	4.19	3.85	1.2	1.21
summer	3.61	4.21	1.43	1.45
Autumn	3.14	1.93	1.15	1.10
Overall	3.20	2.75	1.24	1.22

Table 5. Values of the *MJH* model for both locations with all the calibrations

Model	a	b	c
Burydah	0.118409	0.204376	-0.52364
Riyadh 3	0.248903	0.003668	-0.03862
Riyadh 14	0.240171	0.003467	-0.03503

The results of the calibration show an improvement in the predictions than the original *MJH* model and the *MAE* values decreased sharply for both the overall *MAE* and the seasonal *MAE*. The overall *MAE* decreased from 3.20 mm day^{-1}for the *MJH* model to 1.24 mm day^{-1}for the *MJH3* model and to 1.22 mm day^{-1}for the *MJH14* model. Both calibrated models performed better than the JH model which had an overall *MAE* of 2.75 mm day^{-1}. For all the seasons, the same trend was noticed especially in the spring and summer when the *MAE* values reduced the most when using the calibrated equations. Although the *MAE* values were reduced and the calibrated equations showed better prediction than both the *MJH* and *JH* equations, still the T test for the predicted ET_O values for the 14 years of data showed a significant difference between the average predicted ET_o from *FAO* value and the average predicted ET_o values using the calibrated equations tables (6 and 7).

Table 6. T test between ET_o from *MJH3* and ET_o from *FAO*

	Variable 1	Variable 2
Mean	3.042154888	3.28238579
Variance	3.460701869	0.43750782
Observations	7456	7456
Pooled Variance	1.949104846	
Hypothesized Mean Difference	0	
Df	14910	
t Stat	-10.50628623	
P(T<=t) one-tail	4.96979E-26	
t Critical one-tail	1.644955831	
P(T<=t) two-tail	9.93958E-26	
t Critical two-tail	1.960123103	

Table 7. T test between ET_o from *MJH14* and ET_o from *FAO*

	Variable 1	Variable 2
Mean	3.042154888	3.174188
Variance	3.460701869	0.407158
Observations	7456	7456
Pooled Variance	1.933929827	
Hypothesized Mean Difference	0	
Df	14910	
t Stat	-5.796942513	
P(T<=t) one-tail	3.44502E-09	
t Critical one-tail	1.644955831	
P(T<=t) two-tail	6.89004E-09	
t Critical two-tail	1.960123103	

Both *MJH3* and *MJH14* predicted the values of ET_O closer to the average values but failed to predict extreme ET_O values. This may be caused by the method of empirical equation development which depends on minimizing the differences between predicted values and the average values of the original data. Still the equation gives a close estimate of the average ET_o, this estimation can be used to generate ET_o values for sites with no metrological data other than temperature records, and dependable values of ET_o can be estimated using statistical analysis of long-term values of such ET_o values.

CONCLUSION

An improved model for the estimation of reference evapotranspiration was developed using the Jensen-Heise equation as a basic model and the least square method. The proposed equation predicted that ET_o values were closer to the values of ET_o predicted by the *FAO* equation than the values predicted by the *JH* equation. This was shown by the lower *MAE* values for both the overall year and the seasonal *MAE* values. The *T* test of the daily values of ET_o showed that both the *MJH* equation and the *FAO* equation values had the same average. Testing the equation in a location 350 km south of the original site indicated that the equation could be used in places with similar metrology but the constants in the equation require local calibration. Calibration of the equation using three randomly selected years and 14 years of data generated results which are very close to each other.

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تقييم أداء نموذج معدل لمعادلة للتنبؤ بالبخر نتح المرجعي تحت ظروف المناطق القاحلة

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تم تطوير وتقييم نموذج للتنبؤ بالبخرنتح المرجعي ETo في المناطق القاحلة. تم تطوير النموذج بناءً على نموذج Jensen-Heise مع معاملات مضافة وتمت معايرة المعاملات الأصلية للنموذج لظروف المنطقة. للتقييم ، تمت مقارنة قيم ETo للنموذج بقيم ETo التي تم الحصول عليها باستخدام طريقة Penman Monteith. تم تقييم النموذج أيضًا باستخدام مجموعة من بيانات الطقس (14 عامًا من البيانات) تم الحصول عليها من موقع 350 كم من الموقع الأصلي. قام النموذج بتحسين التنبؤ في الموقع الأصلي لتقليل متوسط الخطأ المطلق الكلي (MAE) من 1.62 باستخدام نموذج Jensen-Heise إلى 0.84 باستخدام النموذج المعدل (MJH). أدت معايرة قيم المعامِلات في الموقع الجديد إلى تحسين أداء النموذج وجعله أفضل في التنبؤ من نموذج Jensen-Heise ، مما أدى إلى خفض MAE الإجمالي من 2.75 لنموذج Jensen-Heise إلى 1.24 و 1.22 لمعايرة 3 و 14 عامًا على التوالي