Irrigation & Drainage Systems Engineering

Research Article Open Access

Performance Evaluation and Development of Daily Reference Evapotranspiration Model

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Abstract

Using agricultural water wisely in irrigated fields is very important, especially with water scarcity in arid and semi-arid countries globally. An accurate irrigation water requirement calculation is required to determine real time irrigation scheduling, in order to apply the specific amount of irrigation water at the right time, and avoid crop growth stress which leads to reduced crop production. The main objective of this paper is to develop a mathematical model to accurately calculate daily Reference Evapotranspiration (ETo) as a first step for the accurate calculation of irrigation water requirements. Also, the model output was compared to ETo estimated using CROPWAT, an irrigation software program used for ETo calculation and irrigation scheduling. The reference evapotranspiration model was built using the Food and Agricultural Organization FAO-56 Penman-Monteith equation with the SIMULINK tool in MATLAB software. The model was validated by comparing daily estimates of evapotranspiration with Class A pan and evapotranspiration gauges in the United States. The results indicated a good fit between daily ETo calculated by the model and that observed from Class A pan and evapotranspiration gauge. There were some discrepancies between measured, modeled and CROPWAT ETo. This model is the first step to calculate accurate irrigation water requirements.

Keywords: Reference evapotranspiration; FAO Penman Monteith; Modeling; Irrigation scheduling; Irrigation water requirement

Introduction

Efficient management of irrigation water involves precise irrigation scheduling. To achieve this, an accurate crop water requirement calculation is required. Irrigation is a practice to apply water to the root zone of a crop to reach field capacity. Water use efficiency is driven by three factors; the specific amount of water applied, the timing of the application, and the efficiency of the irrigation method. Irrigation scheduling aims for yield maximization, high irrigation efficiency, and crop quality improvement by adding the appropriate amount of water to the crop in order to bring the soil moisture to the desired level. Crop water requirement is the aggregate volume of water needed to satisfy the evapotranspiration from a specific crop. Crop water requirement varies in two dimensions, spatial and temporal. Reference evapotranspiration is the proportion of evapotranspiration from a uniform reference crop with a crop height 0.12 m from an extensive surface of a green grass of uniform height, well irrigated, actively growing, and completely covering the soil. Reference ET is a major factor required for irrigation water requirement calculations and crop irrigation scheduling. Mathematical modeling is an essential tool to estimate ET and crop water requirements for best water management practices, and further, it is important for irrigation scheduling and irrigation water management.

The objective of this research was to develop a tool to: (1) simulate daily reference ET (ET_o) using real time climatological data, rather than using historical climate data such as that in CLIMWAT, and (2) calibrate it to accurately calculate daily ET_o as a first step for accurate calculation of irrigation water requirements. This study contains two parts, the first, to build the reference evapotranspiration model using the United Nations Food and Agricultural Organization Penman-Monteith (FAO56-PM) equation. This was done using the SIMULINK tool in MATLAB software. The model was validated by comparing daily ET_o calculated by the model versus evapotranspiration using a Class A evaporation pan and evapotranspiration gauges in the United States. The second step is a *comparison* of monthly ET_o estimated from the model using daily data obtained from weather stations with both ET_o measured from the evaporation pan and ET_o calculated using CROPWAT.

Background

Evapotranspiration is the primary consumer of irrigation water and rainfall from an agricultural field. A correlation between evapotranspiration and crop yield has been published for different ET levels and their effects on crop yield [1]. Evapotranspiration is a driving factor for both hydrological and climatological research, in addition to irrigation management [2]. ET determination is commonly preceded by estimation of ET_o [3].

ET model validation requires measurements of evapotranspiration. ET models are often used due to the difficulty and cost of ET measurement. There are different ways for directly measuring evapotranspiration, for example weighing lysimeters and eddy covariance. Indirect measurement includes soil water balance and surface energy balance, using conservation of mass and energy balance [4]. With advances and technology improvement in data acquisition and measurement, improvement of ET estimation is possible, especially with measurement of near vegetation surface climate elements and surface energy exchange [5].

ET_o estimation from weather data has been used in different applications of crop water requirement and irrigation water management calculations. In developing nations, where there is a shortage of direct measurements of ET using lysimeters or soil moisture balances, most irrigation consultants estimate ET_o based on meteorological data. The Penman–Monteith FAO 56 (PMF-56) equation is recommended for

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Received January 22, 2016; **Accepted** February 25, 2016; **Published** February 29, 2016

Citation: Hashem A, Engel B, Bralts V, Radwan S, Rashad M (2016) Performance Evaluation and Development of Daily Reference Evapotranspiration Model. Irrigat Drainage Sys Eng 5: 157. doi:10.4172/2168-9768.1000157

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the estimation of reference evapotranspiration and provides reliable ETo values under different climate conditions [6,7].

The Penman–Monteith FAO 56 is recognized worldwide as a reasonable ET_o estimator in comparison with other methods [8]. Most irrigation planners, climatologists, hydrologists and agronomists use it in research field applications [9]. The PMF-56 has a major disadvantage as it needs multiple meteorological elements, and this is not applicable in developing countries [10,11]. There are several models to estimate ET_o, such as Ref-ET and CROPWAT. CROPWAT primarily imports weather data from CLIMWAT, which is a database containing historical climate data. Ref-ET is software, but it must be purchased to obtain its full capabilities. Ref-ET also contains a variety of equations that can be used to estimate ET_o thereby facilitating comparison of different ET estimation methods at a location.

ET_o can be estimated using weather station data, measured by Bellani plate evapotranspiration gauges, or obtained from the evaporation pan multiplied by K_{pan} factor [12]. Evapotranspiration estimation models require input data that are field observations and derived or assumed parameters. Field measurement of meteorological variables is a critical part of the evaporation estimation process. Measurements and recording errors in field variables result in ET estimation errors [4]. There has been significant progress in the capability of near surface meteorological variable measurement such as temperature, precipitation, wind speed, solar radiation, and humidity using automated climate stations [13]. This has the effect of simplifying ET model usage.

The Bellani plate evapotranspiration gauge (atmometer) is another way to measure ET_o by using a plate to simulate water evaporation from a green surface to match short canopy reference evapotranspiration. The ET measured using a Bellani gauge is inaccurate, especially in humid climates, where poor performance occurs on rainy days. The ET_o estimated using ET gauges is 27% lower than the FAO56-PM ET_o. The correction factor between the evaporation rate (E_A) and ET_o was 0.84 as expressed in the following $E_A/0.84 = ET_o$ [14].

Models for Irrigation Planning

CROPWAT

CROPWAT uses the Penman-Monteith equation [15] for computing reference evapotranspiration. The reference evapotranspiration is used to calculate crop water requirement and irrigation scheduling [15,16].

CROPWAT has a user friendly interface with input and output menus. The input data consists of the following: monthly weather data to estimate ET_o, monthly rainfall data, cropping pattern and crop coefficient data, and soil type. The irrigation schedule is calculated based on the input data. Different methods are used in CROPWAT to calculate irrigation scheduling; once an appropriate method is selected, the irrigation dates and amounts will be calculated [17]. CROPWAT provides results at a monthly time step, which is not accurate enough for real time irrigation management. CROPWAT can provide outputs with a daily time step, but the data must be entered manually, which is time consuming and prone to errors.

CLIMWAT is a meteorological dataset used to export the input files to CROPWAT to calculate the crop water requirement and irrigation scheduling for different crops for more than 5000 stations worldwide. CLIMWAT exports the following climate elements: Monthly maximum and minimum temperature (°C), wind speed (km/day), relative humidity (%), solar radiation (MJ/m^2/day), sunshine hours per day, monthly rainfall (mm month^{-1}), effective rainfall (mm month^{-1}) and calculated reference evapotranspiration (mm day^{-1}).

The CLIMWAT historical monthly data typically is not accurate enough to calculate reference evapotranspiration, which leads to inaccurate estimates of ET_o, causing stress on plants due to insufficient irrigation or over irrigation, resulting in yield losses or crop failure. Irrigation water requirement calculated based on daily weather data is more accurate than average monthly data because the actual need for plants is determined. All required weather elements are not available in each CLIMWAT station, and many weather stations merely measure air temperature and precipitation. As a result, the information in such datasets should never replace the actual data [18].

ET_o observed from pan evaporation

In many regions, evaporation pans are widely used because of the simplicity of the method, as well as being inexpensive in comparison with ET measurement and its application. Evaporation pans are useful in some locations, where no weather data is available. In Egypt for example, agronomists used the evaporation pan for Egyptian clover and maize irrigation scheduling in Kafr El-Sheikh and Giza 1 in Giza [19].

The depth of water evaporated from the pans is easy to measure by subtracting the new depth of water from the initial water depth. The pan measurement is a combination of different climatological factor effects on a free open water surface, including wind, radiation, humidity, and temperature. In recent years, the evaporation rate from pans has been the subject of much debate. However, there are other considerations which contribute significantly to water loss from open water surfaces rather than from crop surfaces. The pan side heat transfer affects the energy balance, and the pan heat storage, which evaporates water throughout the night. Also, turbulence variances, air temperature, and relative humidity differ beyond the water and crop surface [20]. Validated a model of evapotranspiration based on the Penman-Monteith method at two locations southern Italy and southern France in Europe, using soybean datasets, permanently stressed, planted in the Mediterranean weather, with a semi-arid and a semi-humid weather, respectively. The model provided good results for the two sites with hourly, daily, and seasonal time scales [21]. Validated an evapotranspiration model using meteorological and lysimeter evapotranspiration hourly data sets at Davis, California, and daily time steps at Policoro, Southern Italy. The model output was validated with the ET estimated using the FAO Penman-Monteith method, and the model reference ET estimate is reasonable on two time steps hourly and daily.

Materials and Methods

In this research, an ET_o model was developed to investigate estimation of daily reference evapotranspiration using meteorological data. To validate the model, ET_o data from the class A evaporation pan at Dubois, Indiana and evapotranspiration gauges at Purdue Center for Research and Education (ACRE), West Lafayette, Indiana, USA, were compared with ET_o estimated by the model in both locations. This model uses the FAO PM-56 as this method fits different locations globally with the same inputs, in addition to having a user friendly interface.

The Simulink tool in MATLAB was used to build the ETo model using the FAO Penman-Monteith equation expressed by [18]. The main inputs of the model are the daily averages of climate elements: maximum and minimum air temperature, air humidity, wind speed, and solar radiation as shown in Figure 1. Also, the latitude, longitude, and altitude are required.

The Penman Monteith-FAO 56 equation:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

Where ET_o is reference evapotranspiration (mm day^{-1}), R_n is net radiation at crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (°C), U_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), e_s-e_a is saturation vapor pressure deficit (kPa), Δ is slope vapour pressure curve (kPa °C^{-1}) and γ is psychrometric constant (kPa °C^{-1}).

For as and bs, average values (as =0.25, bs =0.50) as recommended by FAO were used [18]. The ET_o model produces daily reference evapotranspiration (mm day^{-1}).

For this research, data was obtained from the NOAA database website and Wunderground database website for Dubois S IN forage farm, IN, USA (Station ID: GHCND: USC00122309) located at 38.46° N and 86.69° W, with 210.3 m elevation above sea level from May 17th to July 31st 2006, May 5th to October 14th 2010, April 12th to September 30th 2011, and May 4th to October 31st 2012. For this data set the missing data was not replaced. For the ACRE site, the data were collected from the Indiana State Climate Office website. Data at the ACRE site was obtained using *a* Bellani plate evapotranspiration gauge (atmometer). ACRE is located at 40.47° N and 86.99° W, with 214 m elevation above sea level for the growing season (May 1st to October 31st, June 1st to October 31st) for 2010 and 2011.

The principle weather parameters considered were maximum and minimum air temperature, air humidity, wind speed, and solar radiation. According to FAO 56, the equations for a Class A evaporation pan with green fetch are indicated as [18]:

$$ETo = K_p \times E_{pan} \quad (2)$$

Where ET_o is the reference evapotranspiration (mm day^{-1}), K_p is pan coefficient, and E_{pan} is the pan evaporation (mm day^{-1}).

Under some conditions, the K_p coefficients may need some adjustment where tall crops surrounded the evaporation pan. The daily average relative humidity, wind speed (U_2) and the upwind fetch distance of the evaporation pan location are factors affecting the Pan coefficient [18,22].

CROPWAT was also used to calculate ET_o for the two sites in Indiana, USA using monthly historical data. The input data was climate, crop, soil and planting dates. The CLIMWAT data set was based on weather station data. With the humid weather in Indiana, solar radiation and other climatic factors are affected by cloud cover. This leads to uncertainty in evapotranspiration estimation occurs.

The Nash-Sutcliffe coefficient (NS) for model performance accuracy was used in the study to validate the ET_o model by comparing predicted and observed ET_o. The Nash-Sutcliffe coefficient is a sign of the model's capability to predict about the 1:1 ratio between experimental and estimated data. Nash–Sutcliffe can be a value from negative infinity to one, efficiency of 1 means an exact ET_o values estimated by the modeled to the measured data, efficiency of 0 means the model forecasts are no more accurate than the mean of the measured data, and efficiency less than zero means the measured mean is better than the model [23].

Results and Discussion

Model validation on a daily basis

The daily ET_o data calculated by the ET_o model for West Lafayette and Dubois, IN USA was compared with the pan evaporation and ET_o gauge observed ET_o values. The results are presented graphically in Figure 2, and the correlation coefficient (R^2) and Nash-Sutcliffe coefficients (NS) are shown. The R^2 and NS for the model and evaporation pan differ by location and year. The figure shows that

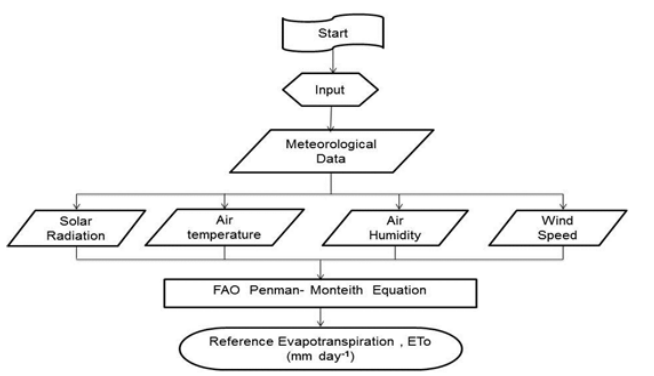

Figure 1: Flow chart for the reference evapotranspiration (ET_o) model.

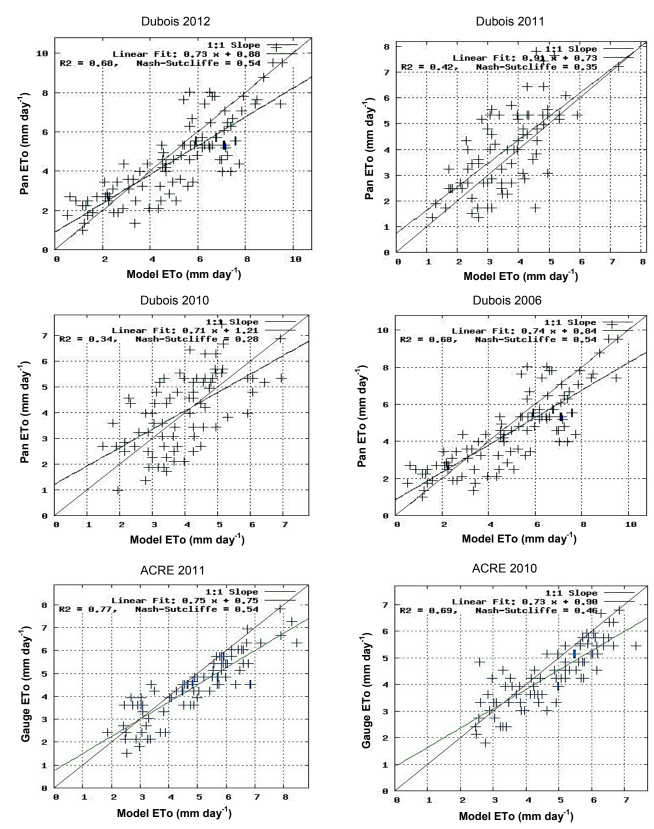

Figure 2: Reference evapotranspiration model validation between measured and simulated daily evapotranspiration from evaporation pan& gauge with model ET_o.

the ET_o values calculated by the ET_o model are in the range of those obtained by pan evaporation and ET_o gauges for most days.

In Dubois, the relationship between ET_o estimated from the model and ETo observed from the pan is linear, with differing R^2 and NS coefficients between different years. The R^2 and Nash-Sutcliffe coefficients were equal to 0.68 and 0.54 in 2012, 0.42 and 0.35 in 2011, 0.34 and 0.28 in 2010 and 0.68 and 0.54 in 2006 between the ET_o model and ET_o pan. The R^2 and Nash-Sutcliffe coefficients for ACRE were 0.77 and 0.54 in 2011 and 0.69 and 0.47 in 2010 between the ET_o model and ET_o gauge. The R^2 coefficient is better for ACRE rather than Dubois and the NS is similar between the two sites in different years.

For the Dubois site, the Nash-Sutcliffe coefficients were 0.54 in 2012, 0.35 in 2011, 0.28 in 2010 and 0.54 in 2006 as shown in Figure 2. For the ACRE site, the NS was 0.54 in 2011 and 0.47 in 2010. In 2012, there was a drought in Indiana, which meant higher temperatures and lower relative humidity than in a typical year. For the drought year, the model performance was good, as the ET_o values from the model were close to the ET_o values estimated from the evaporation pan and gauges. However, in 2010 the average temperature was much lower and humidity was much higher than 2012 and 2006, which appears to impact model performance in those years. Lower temperature and high humidity results in reduction of the evaporation rate from the pan and gauges, which leads to increases in the differences between the ET_o estimated from the model and the pan.

For hydrology related model performance, the NS values larger than 0.4 and R^2 values greater than 0.5 are considered acceptable model performance. Satisfactory models achieving a NS coefficient higher than 0.5 and a R^2 higher than 0.6 specify acceptable model [24].

The minimum and maximum differences between the calculated from the model and measured from the pan and gauge based on daily values are in the range of -3.96 to 5.11 mm with an absolute average of 0.56 mm in 2012, for 2011 in the range -4.94 to 5.8 mm with an absolute average of 0.10 mm, for 2010 in the range -1.49 to 4.46 mm with an absolute average of 0.66 mm, and for 2006 in the range -0.61 to 5.09 mm with an absolute average of 1.34 mm for Dubois. However, in ACRE, the differences between the ET_o estimated from the model and determined by the gauge ranges from -1.24 to 2.31 mm with an absolute average of 1.24 mm in 2011 and for 2010 the range was from -2.24 to 1.90 mm with an absolute average of 0.51 mm.

The results of this work indicated the ET_o model provided reasonable estimates of ET_o as shown in Figure 2. There is a slight variance between ET_o estimated from the model and ETo obtained from the evaporation pan. The model provides higher ET_o than the pan, likely due to the humid weather and the cloud cover in the study area; these results agree with the findings of [25]. In Indiana, the weather is humid and this may be the key reason that the model performance in humid years was not as accurate as performance in dry years. The high humidity reduces the evaporation from the pan, which means there is a lower evaporation from the pan.

At ACRE, the required dataset was obtained using one source, which is the weather station located in the center of the site. However, in Dubious the required dataset was obtained using two different sources - NOAA and Wunderground. The use of two sources means the use of different locations and instrumentation for each source, potentially leading to different accuracies and measurement approaches.

Model performance on a monthly basis

In order to compare the monthly performance of the model versus the evaporation pan, gauge and CROPWAT software. The daily ET_o data was being averaged on a monthly basis for the evaporation pan, the model, and compared with CROPWAT ET_o in DUBOIS site, and for ACRE site, the evaporation gauge, the model, and compared with CROPWAT ET_o software as shown in Figure 3 .There are differences between the monthly ET_o from pan, gauge, model, and CROPWAT software for both of the locations. The daily ET_o estimated from the model is mostly higher than ET_o from evaporation pan and gauge, and the monthly average is nearer the average of ET_o pan than the monthly ET_o from CROPWAT. These results prove a better performance of the ET_o model with pan evaporation. The model provided a more accurate estimate with an evaporation pan data than CROPWAT.

As shown in Figure 3, in Dubois for 2012, the model provided a good estimate of ET_o, and there was a peak for the ET_o model in July as there were high temperatures, which increased the predicted ET by the model. The ET_o estimated from the model is higher than the ET_o obtained from the pan and ET_o calculated from CROPWAT from May to July, especially during July as the air temperature is higher than May and June, and the model sensitivity is much higher to the climate elements than the pan. However, ET_o estimated from the model in September and October is closer to the ET_o obtained from the pan than CROPWAT. For 2011, the ET_o simulated from the model was higher than ET_o from the pan and less than CROPWAT from May until July, and then the model gives higher estimates in August and then returns in September to be closer to CROPWAT than the pan. In 2010, the ET_o estimated from the model is higher than both ET_o estimated from the pan and calculated from CROPWAT from May through September. These results are due to higher wind speed than previous years. Then, a decline occurred in the ET_o estimated by the model in October to levels approximately the same as ET_o from the pan and CROPWAT. Finally, in 2006, the ET_o estimated from the model is nearer ET_o obtained from CROPWAT than the pan. However, the ET_o estimated from the model is less than ET_o CROPWAT values in June, although it is higher than ET_o calculated from CROPWAT in May and July.

In ACRE for 2011, the model estimated a higher ET_o than the gauge and CROPWAT from June to August, then the model estimates declined, with values relatively similar to ET_o measured by the gauge. In 2010, the model estimated values were larger than those for the gauge, except in June and October when the values of the ET_o model and the gauge were similar.

With respect to use of CLIMWAT and CROPWAT software with average monthly meteorological data, there are differences between monthly ET_o calculated from CROPWAT, pan observations, and the gauge. Significant underestimation of ET_o with similar models was detected in analyses for arid and semiarid sites under Mediterranean climate conditions [20,21,26,27].

This could result in an incorrect irrigation water requirement calculation when using CLIMWAT and CROPWAT software for an estimated ET_o. Over-irrigation results in an excess of water, which is priceless for many arid nations, with additional potential for increasing of groundwater level and unwanted wetness of the root zone. Under-irrigation during the growing season causes plants to wilt. Extended periods of under-irrigation may result in yield loss or crop failure.

Figure 3 illustrates the relationship between monthly reference evapotranspiration (ET_o) measured from evaporation pan and gauge, simulated by the reference ET_o model and calculated by CROPWAT. There are differences between monthly ET_o due to the use of old meteorological data in CLIMWAT. This result agrees with [28].

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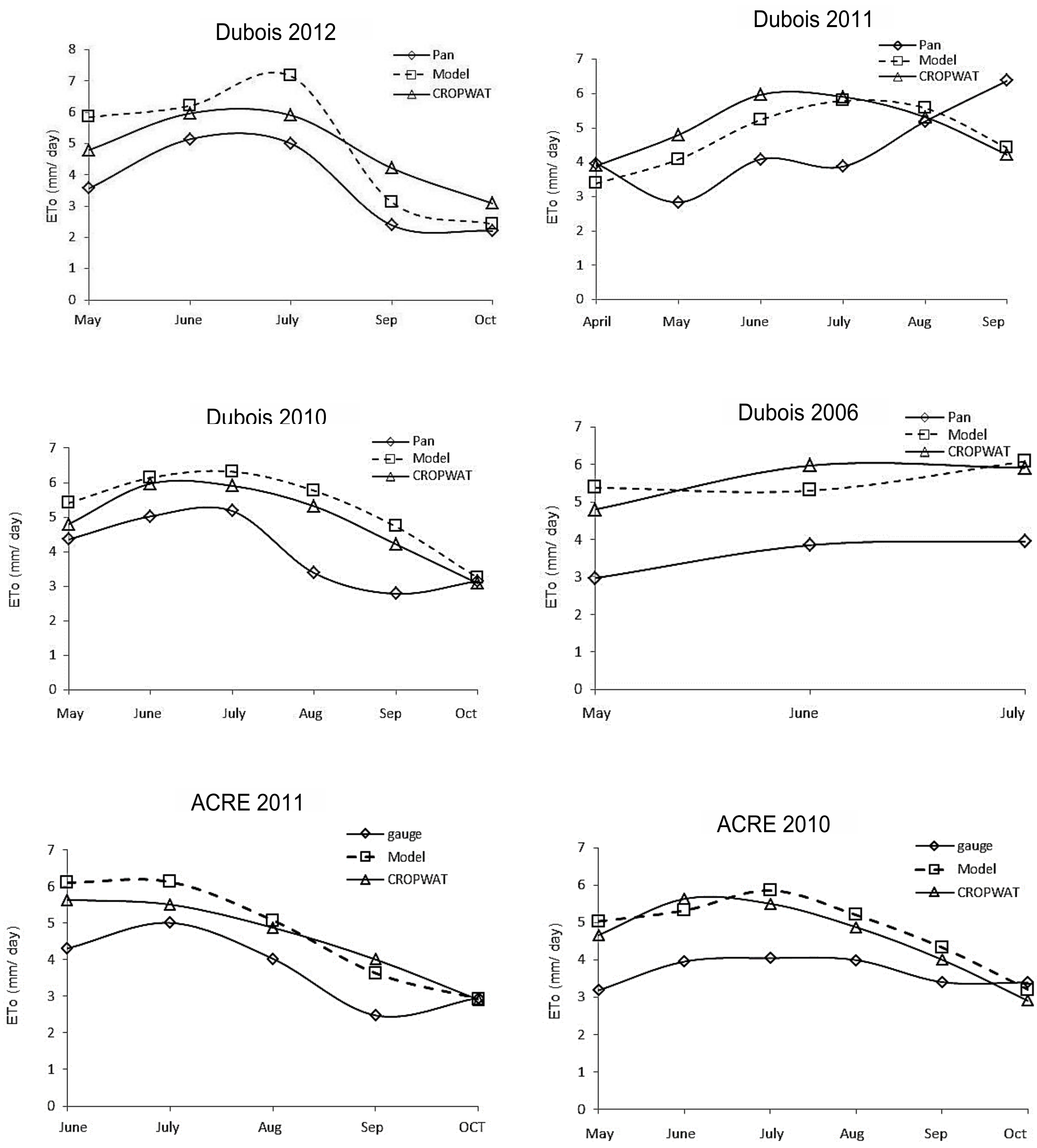

Figure 3: Monthly reference evapotranspiration estimated from the pan, model and CROPWAT software.

CLIMWAT is a reasonable meteorological dataset that contains data from 3262 climatological locations globally. In this study, CLIMWAT data was exported to CROPWAT to calculate ET_o, then was compared with ET_o estimated from the model and ET_o obtained from the gauge as shown in Figure 3. In this case, CROPWAT underestimated ET_o values as cloud affect was neglected on CLIMWAT, which reduced solar radiation. However, it may be precise when using an existing weather dataset. These results should use for preparatory applications because mean monthly data only used in this approach. These results agree with those of [18].

Summary and Conclusions

For accurate irrigation water requirement calculations, a mathematical model was built to estimate daily reference evapotranspiration from meteorological data. The model was built using the Food and Agricultural Organization Penman-Monteith equation with the SIMULINK tool in MATLAB software. The model was validated for two locations in the USA.

The process of developing the proposed model is based on the equations presented by the FAO Penman-Monteith method. The ET model uses public climatic variables measured beyond the crops. The model uses daily temperature (max, min, dew), sunshine hours and wind speed to estimate ET_o. The ET_o model simulates the daily reference ET amount from a short, green grassland. Then, the model was validated by comparing daily data between the ET_o model with ET_o pan evaporation and ET gauge in the USA.

The results of the analyses comparing model ET_o estimate with pan evaporation demonstrate that the model performed well in estimating daily ET_o from meteorological data. The model gives accurate estimates based on a daily and monthly basis, which lead to improved accuracy in ET_o estimation compared with using old weather data such as the CLIMWAT dataset. The model performance was more accurate in ACRE than Dubois, based on daily calibration between ET_o estimated from the model versus ET_o obtained from the evaporation pan and gauge, respectively. The CROPWAT estimate is typically lower than the estimate from the model created in this study and measured ET_o.

Finally, the model is a useful tool for calculating reference ET, which is needed for the accurate calculation of irrigation water requirements. Nonetheless, more calibration of this model is necessary to evaluate its appropriateness for diverse regions beyond the study areas of the United States when applied to irrigation scheduling.

Acknowledgment

We thank Prof. Mahmoud Hany Ramadan (passed away) for his feedback and suggestion to improve the data set analysis and the text. This research was supported by a governmental general mission scholarship administrated by the Egyptian Cultural and Education Bureau, Washington, DC, and by the Department of Agricultural and Biological Engineering at Purdue University.

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Citation: Hashem A, Engel B, Bralts V, Radwan S, Rashad M (2016) Performance Evaluation and Development of Daily Reference Evapotranspiration Model. Irrigat Drainage Sys Eng 5: 157. doi:10.4172/2168-9768.1000157