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Estimating Reference Evapotranspiration Using Penman-Monteith (FAO-56-PM) Method from Limited Data in Fan and Pad Greenhouses

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ABSTRACT

Determination of reference evapotranspiration (ETo) in required for design, management and scheduling of irrigation water in fan and pad greenhouses. In actual practice estimation of (ETo) in fan and pad greenhouses is often made using the Penman-Monteith FAO-56-PM; method from external meteorological data. This requires availability of accurate meteorological input data (temperature, relative humidity, wind speed, and solar radiation). This is constrained by lack of such data which is a common problem in developing countries. In this study the proposed procedure to estimate ETo is based on using limited data of outdoor historically recorded climate elements of only temperature wind speed, and site characteristics (altitude, latitude and sun shine hours). In the proposed method radiation is to be predicted from data of air temperature difference rather than its direct measurement. This because radiation measurement using pyranometers and net radiometers is borne to errors calibration errors commonly plagued by hysteresis, and nonlinearity. The obtained results of the proposed alternative procedure were statistically validated in comparison with the standard method (FAO 56 PM) using unlimited input data measured inside the greenhouse and in reference to a directly measured ETo values by class-A-evaporation pan. The performance of the developed model was evaluated by the determination coefficient of the regression "R^2 for goodness-of-fit" and by using the Root Mean Square Error (RMSE). The needed data is collected during three years in three sites in Khartoum North-Sudan *El Alafoon*, *Halfaya*, and *Shambat*. In each site three greenhouses were employed, and data is taken every three days for three months in each year. The obtained result reveals that the proposed limited data procedure to estimate the ETo inside greenhouses agree on statistical basis well with both pan measurement and PM estimation from measured indoor climate variables. The study reveals importance

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of temperature data for estimating ETo in greenhouses and calls for insuring high quality temperature data for calculating ETo in fan and pad greenhouses.

***Keywords*:** Fan and pad, greenhouses, reference evapotranspiration, limited meteorological data, Penman-Monteith, data scarcity

1. INTRODUCTION

Determination of reference evapotranspiration (ETo) is crucial component in understanding hydrology [1], hydro informatics [2], water resources management [3], agricultural management [4], crop simulation models [5], climatology [6], ecohydrology [7], and biodiversity [8]. Determination of ETo is fundamental element in sizing irrigation equipments and in irrigation scheduling in greenhouse in areas with limited water resources. For designing a new greenhouse in a new area the current practice of determining ETo from external climate elements result in over estimating ETo [9]. The frequently recommended standard procedure to estimate ETo is to employ FAO-56-PM method [10-12]. The FAO 56 PM is based on a four main climatic variables (temperature, relative humidity, wind speed, and solar radiation).

The main constraint to use the FAO-56 PM equation is that it requires numerous weather data that are not always available for many locations especially in developing countries To solve the problem, [10] recommend a procedures to estimate the parameters of the FAO-56 PM equation in open field with some missing weather data. [1] applied the limited data FAO -56 - PM procedure to estimate ETo for six humid weather stations from Serbia, South East Europe. They reported that FAO-56 reduced-set PM ETo estimates were in closest agreement with FAO-56 full set PM ET0 estimates at the most of locations. There are many alternative temperature-based approaches to estimate ET0 in a situation of lack of all input data to apply FAOPM model [13-15]. Most of these models are empirical in nature and site specific. There are various soft ware's available to estimate ETo with the full input information and for open field while a few software is available that depends on temperature as fundamental data for processing. ETo. [16-19].

The procedure adopted in this study for estimating ETo is based mainly on air temperature because, temperature is the sole input of ETo process [13], and the air temperature data are more readily available in most of the meteorological stations compared to other weather data (solar radiation, sunshine hours; relative humidity and wind speeds) that are required by models.

There is no software to best of the writer’s knowledge that estimate ETo based on basic geographical parameters and temperature input for greenhouses. The main objective of this study was-to examine whether it is possible to attain the reliable estimation of ETo under greenhouse conditions using limited weather data.

2. MATERIALS AND METHODS

2. 1. Characteristics of Study Area

This study is located in Khartoum North-Sudan (15.40 N Latitude, 32.32 E Longitudes and altitude 380 m above "msl") at three sites *(El Alafoon, Halfaya*, and *Shambat*) .Climate variables inside and outside greenhouses were collected during three years (2020, 2021 2022) in April, August and November from typical three fan and pad controlled greenhouses per site.

The specifications of each house includes:, a galvanized frames (38 × 8.5 × 2.5 m), double layers of polyethylene cover fan and pad cooling system, drip irrigation system (Pipe with 3/4 in diameter and 35 m length, nozzles 50 cm apart and water sump with a pump). The instruments used for measuring climate variables were installed inside and outside each house, and measurements were made in triplicate. They include a class A-pan, for direct measurement of ETo, Air temperature (T_{max},T_{min}) and relative humidity were measured by means of a Campbell Scientific CS-215 combined probe with radiation shield. A Met-One 034B Windset anemometer was used to measure wind speed. Solar radiation was measured using a CS300 Apogee pyranometer manufactured by Campbell Scientific [17].

2. 2. ETo calculations using Simplified Procedure:

Daily ETo was calculated for each greenhouse by means of the FAO 56 PM equation [10]:

$$ET_0 = \frac{0.408A\Delta(R_n - G) + \gamma\frac{90\theta}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{--------------------------- (1)}$$

where: ETo is the reference evapotranspiration (mm day); Rn is the net radiation at the crop surface (MJ m), which was estimated according to the procedures outlined by [10]; G is the soil heat-flux density (MJ m^2/day). ETo calculations were made using measured climate variable inside and outside each greenhouse. In accordance with [10,13] the simplified procedure for estimating ETo using Penman-Monteith (FAO -56) with limited data is shown in process flow chart (Figure 1).

i) Input data: The monthly average outdoor greenhouse maximum, minimum temperature, in degrees Celsius (°C) and site characteristics (Latitude and altitude). Air temperature is the essential climate parameter for estimating reference evapotranspiration. Their measurements are simple, collected in most weather stations, easily accessed and with no expected high errors in contrast to the other weather parameters. For estimation of wind speed ether input the wind speed from local station in the range of 2 to 0.5 m/s or just use 2 m/s due to the small crop height (0.15 m) and reduced speed frequently encountered inside the greenhouse. Taking the Location input data (altitude (z), and latitude) the associated intermediate parameters estimated from maximum, and minimum temperatures are depicted in the flow chart of figure 1 and detailed by utilizing the following relations [[10,20,21]. average temperature,

T, (o C) = (T_{max} + T_{min})/2. --- (2)

ii) Estimating Wind speed: Wind speed data need to be adjusted to the standard height of 2m. The global default wind speed of 2 m/ s recommended by Allen (1996) was not used because of poor results reported by Trajkovic (2005)

iii) Estimating Missing Vapor Pressure Data: Allen (1996) reported that accurate measurement of vapor pressure (VP) is difficult to measure; while measurement of relative humidity (RH) by electronic sensors is commonly plagued by hysteresis, nonlinearity and calibration errors.

Alternative avenue is to estimate (VP) by assuming minimum air temperature is equal to dew point temperature [13]. If T_{min} is used to represent T dew then:

$$VP (T_{min}) = 0.611 \exp [(17.27 * T_{min}) / (T_{min} + 237.3)] \text{ ---------------------------(3)}$$

where: VP (T_{min}) = actual vapor pressure obtained from minimum air temperature (kPa); Slope of the saturation vapour pressure versus temperature curve,

$$D = (2503 \exp (17.271/T_{min} + 237.3)) / (T_{min}+ 237.3)^2 \text{ --------------------------- (4)}$$

Latent heat of vaporization of water, $k = 2.501 – (2.361* 10^{-3}) *T$ --------------(5)

Psychometric constant, $c = 0.000665*P$ --(6)

Actual vapour pressure,(ea):

$$ea = 0.611 \exp (17.271/T_{min} + 237.3))/ (T_{min} + 237.3) \text{ ------------------------------(7)}$$

Saturation vapour pressure,es:

$$es =0.611 (\exp (17.271T_{max}/T_{max} + 237.3)) + \exp (17.271T_{min} /T_{min} + 237.3) \text{ ----(8)}$$

***iv)* Estimating Missing Radiation Data:** Solar radiation is often estimated from sunshine data using Angstrom equation:

$$Rs = (0.25+ 0.5* (n/N)) * Ra \text{ ---(9)}$$

where: Rs = solar radiation (MJm−2 day −1); n = sunshine hours (h /day); N = daylight hours (h /day); Ra = extraterrestrial radiation (MJm −2/ day). Extraterrestrial radiation and daylight hours are computed as a function of the local latitude and Julian data [10,22,23].

Extraterrestrial radiation,

$$Ra = (24 \times 60/\pi) * Gsc * dr * [\omega s \sin (\varphi) \text{ Sin } (^{\delta}) + \text{Cos } (\varphi) \text{ Sin } (^{\delta})]. \text{ --------------(10)}$$

where: Ra= extraterrestrial radiation [MJ m-2 day-1], Gsc = solar constant = 0.0820 MJ min-1. Dr = inverse relative distance Earth-Sun (rad), S= sunset hour angle (Equation 25 or 26) [rad], Φ= latitude [rad], σ = solar declination [rad].

Solar radiation,

$$Rs, = 0.16*Ra * (T_{max} – T_{min})^{0.5} \text{ ---(11)}$$

Clear sky radiation,

$$Rso = (0.75 + 2 \times 10^{-5}) *Z) Ra,$$

where z = altitude above sea level (m) ---(12)

Net long wave radiation,

$Rnl=\sigma * (((((T_{max}+273.16)^4) +(273.16+T_{min})^4)/2) *(0.34 – 0.14 *(ea^{0.5})) * ((1/35/Rso)-0.35))$ --- (13)

Net shortwave radiation, $R_{ns} = 0.77R_s$ ---(14)

Net radiation, $R_n = R_{ns} - R_{nl}$ ---(15)

where sunshine data are absent it is possible to use the maximum and minimum temperature difference to estimate solar radiation (Hargreaves et al. 1985; Allen 1997):

Rs(T) = [K (Tmax – Tmin) ^ 3.5] *Ra. --(16)

where Rs(T) = estimated solar radiation (MJm^−2 day^−1); Ra = extraterrestrial radiation (MJm^−2 day^−1); Tmax and Tmin = maximum and minimum air temperature (°C); and K= adjustment coefficient with K = 0.16 for “interior” locations and K = 0.19 for “coastal” locations (Allen et al. 1998).

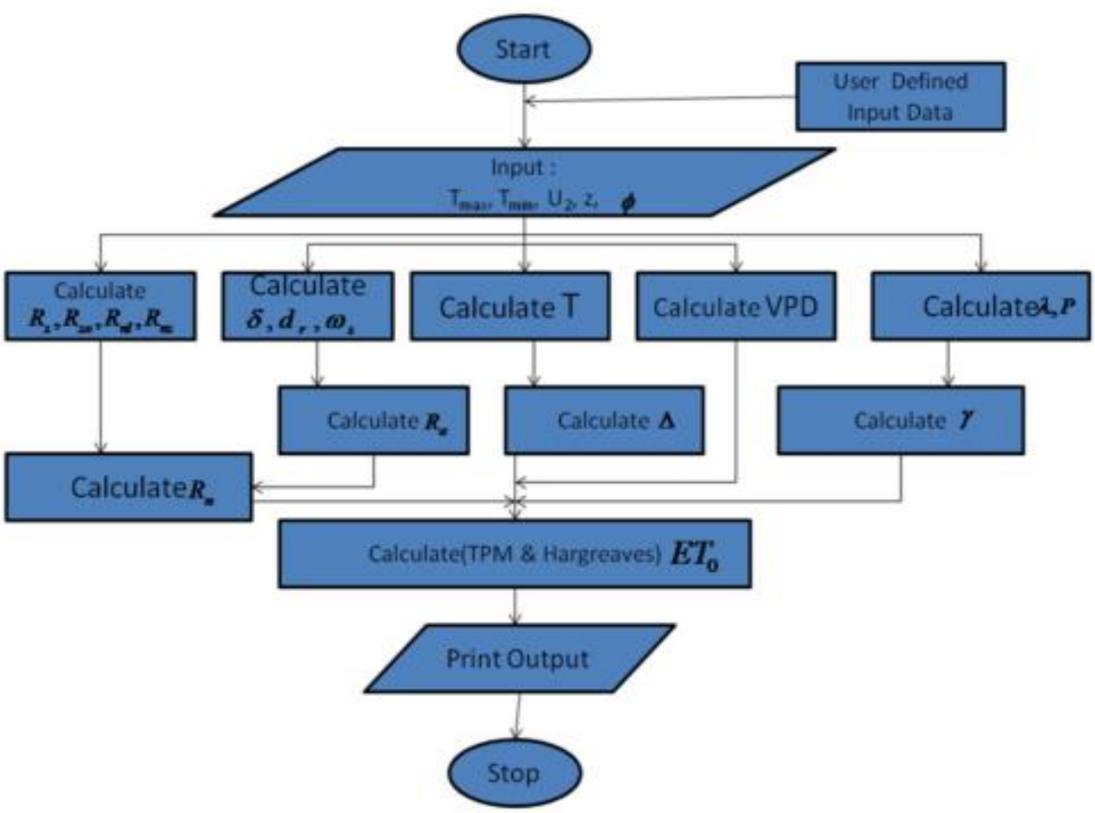

Figure 1. Process flow chart of the limited data model for estimating Reference Evapotranspiration Using Penman-Monteith (FAO -56-PM – [28]).

2. 3. Evaluation Parameters

Evaluation of predictability of the proposed limited data procedure is based on the assumption that Eto measured by Pan is standard reference value followed by Eto estimated from inside data. Several statistical indicators can be considered for the evaluation of ETo estimates. In this study the statistic criteria used were root-mean-squared error (RMSE), Nash–Sutcliffe efficiency (NSE) and Chi-squire-test.

i) Root-mean-squared error (RMSE),

$$RMSE = [(\sum_{i=1}^{k} (Pi - Oi) ^\wedge 2) / k] ^\wedge 0.5 \text{ -- } (17)$$

where RMSE = root-mean-squared error (mm day−1); Oi = ith observed data (ET0 estimated by the FAO-56 full set PM equation in mm /day); Pi = ith predicted data (ET0 estimated by the FAO-56 temperature based limited data method, in mm / day), and k = total number of observations

ii) Nash–Sutcliffe efficiency (NSE)

The Nash-Sutcliffe model efficiency coefficient (NSE) is commonly used to assess the predictive power and accuracy of hydrological or estimation models. The Nash–Sutcliffe efficiency is calculated as one minus the ratio of the error variance of the modeled time-series divided by the variance of the observed time-series. It is defined as [29]:

$$NSE = 1- [(\sum (Qo -Qm) ^\wedge 2)/ (\sum (Qo - Qavg) ^\wedge 2)] \text{ ------------------------------ } (18)$$

where: Qavg is the mean of observed ETo, and Qm is modeled Eto. While Qo is observed ETo at time t.

Nash-Sutcliffe efficiencies can range from -infinity to 1.0. An efficiency of 1.0 corresponds to a perfect match between model and observed data, whereas an efficiency less than 0.0 occurs when the observed mean is a better predictor than the model. In reality, NSE = 0 indicates that the model has the same predictive skill as the mean of the time-series in terms of the sum of the squared error.

iii) Chi-squire-test ($\chi 2$):

A chi-square test is a statistical test that compares observed and expected results of random, independent, and mutually exclusive data [30]. The chi-square goodness of fit test is used to test whether the frequency distribution of a categorical variable is different from your expectations. It can be used to test hypotheses of independence is used to test whether two categorical variables are related to each other, find the relationship between variables, or measure the goodness of fit, the significance of variance, or the homogeneity of data. It calculates a test statistic that reflects the size of the discrepancy between the actual and the predicted data. The chi-square test ($\chi 2$) is defined as:

$$\chi 2 = \sum (((O - E) ^\wedge 2) / E) \text{ --- } (19)$$

where: X2 =is the chi-square test statistic, Σ is the summation operator (it means "take the sum of"), O is the observed frequency, E is the expected frequency. The larger the difference between the observations and the expectations (O – E in the equation), the bigger the chi-square will be. To decide whether the difference is big enough to be statistically significant, you compare the chi-square value to a critical value.

3. RESULTS AND DISCUSSIONS

Table 1 shows performance of the limited data procedure in predicting ETo in comparison with pan direct measurement and with indoor complete climate data PM estimation method using root-mean-squared error (RMSE). The low values of the (RMSE) for individual months or for mean values indicate close agreement of the proposed Limited data procedure to estimate indoor ETo with pan measurement and with PM prediction. Similar results were reported by [27].

From the results given in table 2 the maximum, the minimum and the range values of Eto measured by pan method are (4.9 ,4.5 and 0.4 mm/day) respectively, and that estimated by the method of PM with complete climate data measured inside the greenhouse are (4.9,4.4 and 0.5 mm/day) respectively. These statistical values indicated a typical result. For Eto estimated with limited data approach the maximum, the minimum and the range values of Eto are (51,4.3 and 0.8) respectively. However, the statistical results obtained by limited data method do not differ much from the other two standard methods. In general, the Eto data estimated by the reduced data approach are slightly higher than those obtained by two other methods. This result is in agreement with the results given by [24 and 25].

Table 1. Comparison of ETo estimated from missing data in with pan direct measurement and with indoor PM estimation using root-mean-squared error (RMSE)

Replication Month - Year		Eto Inside Pan Measured	Limited data Predicted Eto	Eto inside` house estimated by PM -56 Complete data	(RMSE) Comparing Limited data method with Pan measurement	(RMSE) Comparing Limited data method with indoor PM estimation
year	Month					
1	1	4.9	4.7	4.8	0.0623	0.0071
1	2	4.7	4.5	4.5	0.0402	0.0073
1	3	4.5	4.3	4.4	0.0305	0.0026
2	1	4.8	5.1	4.9	0.0700	0.0452
2	2	4.7	4.9	4.7	0.0242	0.0585
2	3	4.8	4.8	4.9	0.0001	0.0001
3	1	4.8	4.9	4.7	0.0008	0.0385
3	2	4.7	5.0	4.9	0.0654	0.0207
3	3	4.8	4.8	4.9	0.0005	0.0006

Mean				0.1808	0.1416
(RMSE) = Root mean square error					

Table 2 shows performance of the limited data procedure in predicting ETo in comparison with pan direct measurement and with indoor PM estimation using (Nash–Sutcliffe efficiency (NSE) and Chi-squire-tests. It is evident from the table that Nash–Sutcliffe efficiency is low for both individual months and for mean values. NSE express the agreement between the limited data procedure and ETo pan measured or PM estimated. This result agrees with [26] and is supported by the no significant differences between them given by Chi-squire test.

Table 2. Comparison of ETo estimated from missing data in with pan direct measurement and with indoor PM estimation using (Nash–Sutcliffe efficiency (NSE) and Chi-squire-tests.

Replication Month - Year		Eto Inside pan Measured	Limited data Predicted Eto	Eto inside` estimated by PM -56	(NSE) Limited data method to Pan measurement		(NSE) Limited data method to indoor PM estimation		Chi-squire-test	
Year	Month								Pan measurement based	PM based
1	1	4.9	4.7	4.8	0.0075	0.0126	0.0071	0.0005	0.0126	0.0052
1	2	4.7	4.5	4.5	0.0560	0.0085	0.0073	0.0303	0.0085	0.0000
1	3	4.5	4.3	4.4	0.1804	0.0068	0.0026	0.1330	0.0068	0.0032
2	1	4.8	5.1	4.9	0.1079	0.0145	0.0452	0.1591	0.0145	0.0035
2	2	4.7	4.9	4.7	0.0163	0.0051	0.0585	0.0381	0.0051	0.0057
2	3	4.8	4.8	4.9	0.0013	0.0000	0.0001	0.0104	0.0000	0.0014
3	1	4.8	4.9	4.7	0.0085	0.0002	0.0385	0.0253	0.0002	0.0030
3	2	4.7	5.0	4.9	0.0519	0.0138	0.0207	0.0881	0.0138	0.0008
3	3	4.8	4.8	4.9	0.0000	0.0001	0.0006	0.0046	0.0001	0.0021
Mean		4.8	4.8	4.8	0.4297	0.0068	0.1806	0.4894	0.0068	0.0028
(NSE) = Nash–Sutcliffe efficiency					0.0685		0.6311		0.0685	0.0278

4. CONCLUSIONS

The FAO-56 PM approach is recommended as the standard procedure for computing reference evapotranspiration. The use of this method is constraint by the lack of all data climate data required for its calculation in many in areas where meteorological information is scarce. The approaches based on limited weather data requirements is possible avenue for estimating ETo. In this study, reduced-set PM approach that depend mainly on using temperature data is postulated in this study and found to be statistically almost typical to both the standard pan evaporation method and the orthodox method of PM with its much weather data. The obtained results strongly support using the FAO-56 PM equation in the absence of the complete weather data set. When using the PM with limited data and temperature-based method the daily values of es, ea, Rn, G, D, c, data and associated intermediate parameters were shown in the text to be estimated from maximum, and minimum temperatures (Tmax and Tmin), and the station location characteristics (altitude “z”, and latitude “u”). The detail of all the inputs parameters of FAOPM and their associated parameters are stated inside the text

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