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Sensitivity Analysis of FAO-56 Penman-Monteith Reference Crop Evapotranspiration Estimation Method to Changes in Meteorological Inputs in Greenhouses

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Abstract: *Estimation of reference evapotranspiration (ETo) using FAO-56 Penman-Monteith method (PM) in greenhouses is critically needed for irrigation scheduling, water management and design of their irrigation system. Such estimation is confronted, in many cases, by unavailability of adequate and precise climatic input data. Hence, this study analyzes the sensitivity of estimating PM - reference evapotranspiration (ETo) to climatic variables in greenhouses with the objective of minimizing the effort in their precise collection without significant loss of information. Therefore, it is assumed that assessing the FAO guidelines to compute ETo when meteorological data are missing could lead to a better understanding of which variables are critically important for reliable estimates of ETo. The needed meteorological inputs in greenhouses on daily basis are the maximum (Tmax), minimum (Tmin) air temperature, solar radiation (Rs), average relative humidity (RH avg), and wind speed (U2 at 2 m height). However, Rs may be predicted from temperature data. Sensitivity analysis in this study is performed by changing (increasing and decreasing) each one of these climate variables by one unit of (10% increment and decrement) for ten cases. Inside house climate data was measured from nine greenhouses in three areas with three houses per areas around Khartoum-Sudan (El Alafoon, Halfaya, and Shambat) for a period of three months in each house. Data where taken at ten day per month (every other three days) at three times per day (morning, mid-noon and evening). Sensitivity of each climate variable to predict ETo was assessed using descriptive statistics (standard deviation - std, coefficient - CV%, and t-test), regression coefficient - r2, slope and Christiansen uniformity of distribution (Ed). The results showed that the change in (ETo) is linearly related to change in all climate variables (r2 = 0.94) except wind speed (U) (r2 = 0.46 to 0.68) at all years. Further, According to relative dispersion (CV %), Std. and t-test ETo is significantly sensitive to (Tmax), (Tmin) followed by (RH) and least sensitive to (U) at all years. This result imply that determination of ETo inside greenhouse require more accuracy in determining Tmax, Tmin, RH than Rs and U2 which can be estimated with reduced precision.*

Keywords: PM; evapotranspiration; Sensitivity analysis; Coefficients; Distribution uniformity, Descriptive statistics.

1. INTRODUCTION

Accurate and consistent estimates of reference evapotranspiration (ETo) in irrigated agriculture are important for planning, design, operation, management and efficient utilization of irrigation and water resources to optimize crop production. Determination of ETo is function of availability of climate input data[1]. In many places in general and for greenhouses in particular determination of (ETo) is constrained by lack of daily data of maximum (Tmax), minimum (Tmin) air temperature, solar radiation (Rs), average relative humidity (RH avg), and wind speed (U2). Their exist multitude of methods e.g. [2-5] for measurement and estimation of ETo using minimum data. These include direct measurement (pan or lysimeter) or indirect estimation techniques (water balance approach). The former is costly and time consuming process [6]. Indirect methods for ETo estimation, include (i) temperature based [7-8], (ii) radiation based [9-10], (iii) evaporation based [11], and (iv) combination method [12]. Usage of indirect methods depends on the easily available meteorological parameters and location characteristics (elevation and latitude[13]. FAO-56 Penman-Monteith (FAO-56 PM) combination method is often used and recommended as standard method to use by the Food and Agriculture Organization (FAO) [14]. However, it is use is criticized by its demand for large number of input data which is not always easily available[15]. Moreover, employment of FAO-56 PM method for greenhouse is constrained by unavailability of climate variables of inside the greenhouse when designing a new one. ETo represent the integrated effect of climatic input variables of temperature (Tavg), humidity (RH avg), wind speed (U), solar radiation (Rs). Among these climatic variables, only some of them exert a greater influence on ETo, as compared to others. Thus, it is very important to understand the effect of making a change in each individual climatic variable on ETo estimation before performing any analysis to determine the degree of accuracy required for measuring the input variable [15].

Sensitivity analysis was recommended by many investigators to quantify the impact of changing each one of the independent variables (input) of a model or equation on the dependent variable (output). It is usually conducted to show that the model behaves rationally and to indicate how accurately values of the inputs need to be measured or estimated. Rational behaviour is generally judged on whether the level of sensitivity of the factors in the model matches what is expected in reality and on whether the relationships between the output and the controlling factors accord with what is observed in the field experiments [16-17]. Sensitivity analysis is planned to be extended to evaluate whether the interaction between factors is correctly simulated and whether a model gives plausible results when operated under extreme conditions. It is also used to identify which processes could be excluded without significant loss of information should a decision be made to simplify a model. The sensitivity of the standardized FAO-56 Penman-Monteith evapotranspiration (FAO-PM ETo) equation to climate variables (wind speed at 2m height _U m maximum and minimum air temperatures, and relative humidity) inside greenhouses has not yet been studied.

Literature review of previous sensitivity analyses revealed that there is no standard or common procedure for computing sensitivity coefficients for climate variables. [18] Define sensitivity analyses by using equations for expressing the rate of change of the independent variable (net radiation, slope of saturation vapor pressure versus air temperature curve, wind profile parameters, and wind coefficient) with respect to each dependent variable (net radiation, slope of saturation vapor pressure). [19] defined the sensitivity coefficient as the slope of the curve of ETo climatic variable being studied. [20] used a partial rank correlation coefficient and the standardized rank regression coefficient to determine sensitivity of the ET to changes in input variables. [21] combined temporal sampling characterized by its relative error and Taylor series to conduct sensitivity analyses. They described the sensitivity coefficient as representing the fraction of change in the climate variable transmitted to the change of ETo.

Most of the earlier studies on sensitivity of combination-based equations were site specific and do not discuss or present daily and seasonal changes of sensitivity coefficients for different climate variables. However, few studies in the past. [22-24] have attempted study of ETo sensitivity analysis in greenhouse. [23] conducted sensitivity analyses for the Penman - Wright alfalfa-reference ETo model to errors in input parameters and weather data using simulation approach for Washington State. He concluded that the Penman-Wright model was most sensitive to the error in maximum and minimum air temperatures, followed by progressively less sensitivity to errors in solar radiation, dew point temperature, and wind speed. . [24] studied the sensitivity of the original Penman-Monteith. [25] ETo model to climatic available energy and vapor pressure deficit and parametric aerodynamic and canopy resistance factors in a semiarid climate for a reference grass surface, grain sorghum, and sweet sorghum in Italy. He stated: For crops under water stress, the most sensitive term was canopy resistance. . [21] studied the effect of the sampling frequency of measured climatic variables on ETo estimates by the FAO-56 PM equation in Belgium .He showed that the (Rs) and (U) were the most sensitive to bias induced by the inadequate temporal sampling frequency. [26] showed that ETo was less sensitive to increase in Rs, followed by (U) in comparison to (Tavg), and increase in vapor pressure had a small negative effect on ETo. [17] used a non-dimensional relative sensitivity coefficient to predict responses of ETo to perturbations in four climatic variables (Tavg, U, RH avg, and sunshine duration). Results showed that RH avg was the most sensitive variable, followed by short-wave radiation, Tavg and U. [27] compared sensitivity of 18 different potential evapotranspiration (PET) models and observed that these PET models were sensitive to significant trends in climate data. . [28] reported that the sensitivity of ETo to wind speed and air temperature decreased and to sunshine hours increased in humid environment. . [29] tested 12 different scenarios considering radiation, relative humidity, and/or wind speed as missing climatic data using guidelines given by the FAO. His results presented that wind speed and actual vapor pressure do not affect ET estimates as much as the other climatic variables. [30] defined absolute sensitivity in term of simplest index of sensitivity coefficient (R) that describes the rate of change in output (increase or decrease) with respect to a change (increase or decrease) in the value of input, but without considering the relative magnitudes of the values. [15] followed a similar approach used by [19] to derive absolute sensitivity coefficients for U2, Tmax, Tmin , RH avg , and R on a daily basis as an average of 3 years each one of three study sites. He found that some of the sensitivity coefficients resulted in very similar but negative values, when the coefficients were derived for decrease in climate variables. Thus, absolute values were taken for consistency reasons. The relative sensitivity index has been modified by [31], by normalizing the input and output in relation to their mean values, to produce an average linear sensitivity index. Thus, the main objectives of this study are to perform sensitivity analysis of the ETo derived using FAO-56 PM method to climate variables (U2, Tmax, Tmin, RH avg, and R) on a daily basis in greenhouses and to quantify daily changes in ETo per unit of change in each climatic variable. The driving purpose is to determine the relative effect and the accuracy required for measuring the input variable on ETo determination

2. MATERIALS AND METHODS

2.1 Study Area and Climate Data: This study was conducted at three study areas (El Alafoon, Halfaya, and Shambat) within Khartoum North (15.40 N Latitude, 32.32 E longitudes and altitude 380 m above "msl") for a period of three months in each year in three houses per area. Each one of the nine greenhouses is equipped with double layers of polyethylene cover, and galvanized frames, fan and pad cooling system, and typical specifications. Relative humidity, wind speed and temperature meter were used to measure the relative humidity and temperature inside and outside of the greenhouse. Pipe of irrigation system is 3/4 in. in diameter and 35 m length was used for the irrigation of the test crop in the greenhouses the pipe has 70 nozzles 50 cm apart and is connected with the water source pump. As recommended by [13] all experiments were conducted in steady state and all of the tests were achieved in triplicates. The measurements were conducted in three years (2020, 2021 2022) in April, August and November each year in each house. The instruments used for measuring climate variables were installed inside and outside each house. These instruments include a class A - pan, for direct measurement of ETo, and air temperature (T), relative humidity (RH), wind speed (U). TemperaturesTmax,Tmin and RH were measured by a thermohygrometer (HMP45AC, Vaisala Inc., Woburn, MA, USA) inst alled 2 m above the ground level. Wind speed (U) was measured using an anemometer (03101 R.M.Young Company, Traverse City, MI, USA). Data where taken at ten day per month (every other three days) at three times per day (morning, mid-noon and evening). Each variable was increased and decreased for each day for a period of 3 months . [19,15].

2.2 ETo Prediction: For this study, daily climate data inside greenhouse was measured from three areas for a period of three months in each house is given in table 1. The daily climatic variables are (temperature maximum (Tmax) and minimum (Tmin), average relative humidity (RH), wind speed (U2), and radiation (Rs). Evapotranspiration was computed using FAO-56-Penman-Monteith method (PM) given by . [14] as:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left[1 + \frac{r_s}{r_a}\right]}$$

Equation 1: Penman-Monteith equation

In the equation, λ= is latent heat of vaporization, Δ= is the slope of the vapour pressure temperature relationship, Rn= is net radiation, ρa= is air density, Cp= is the specific heat of dry air, es = is saturation vapor pressure, ea= is actual vapor pressure of the air, rs= is aerodynamic resistance, ra = is bulk surface resistance and γ = is psychomotor constant.

Table 1: Monthly average climate data inside greenhouse measured in the three areas for a period of three months for three houses

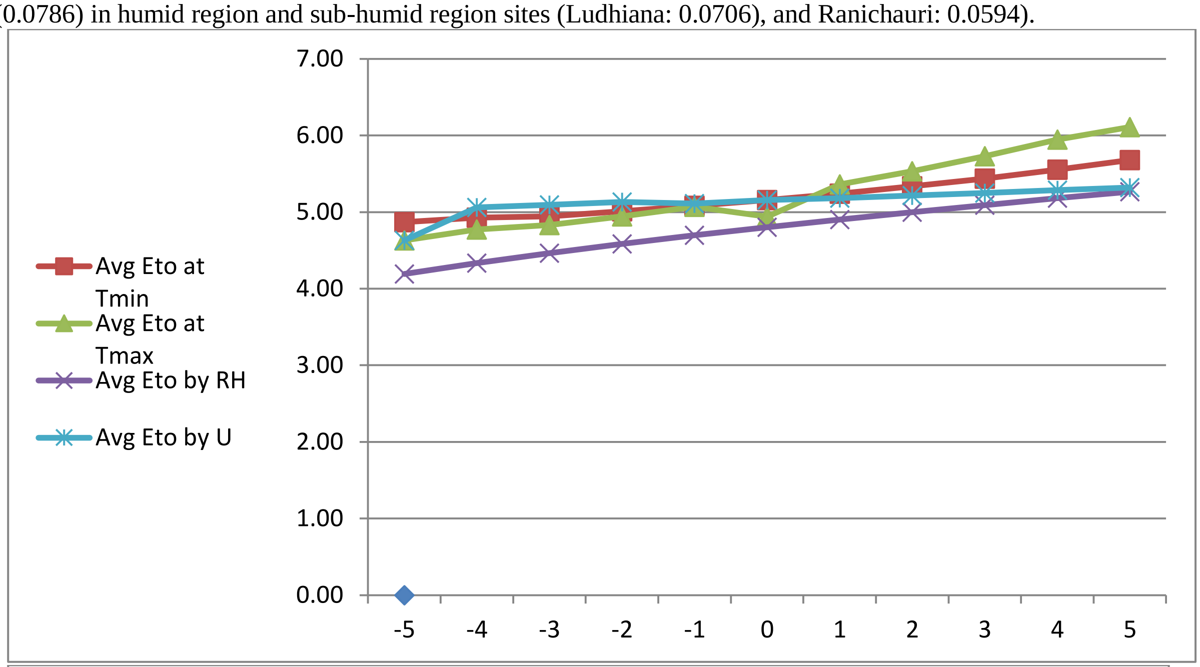
Particular	**Year 1**			**Year 2**			**Year 3**		
Month No	4	8	11	4	8	11	4	8	11
Tmax °C	32.0	31.0	31.0	30.8	30.8	30.0	29.0	29.4	29.3
Tmin °C	26.3	25.2	25.2	25.4	25.4	25.6	26.2	25.9	24.0
Vapour Press avg (ea)	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85
Avg daily wind speed (U2)	0.70	1.01	1.01	0.80	0.80	1.01	1.14	1.00	0.91
RH %	58.0	73.8	73.8	70.1	70.1	73.8	83.2	72.6	68.0
Duration sunshine hr	9.8	8.6	8.6	8.6	8.6	8.6	9.8	8.6	8.6

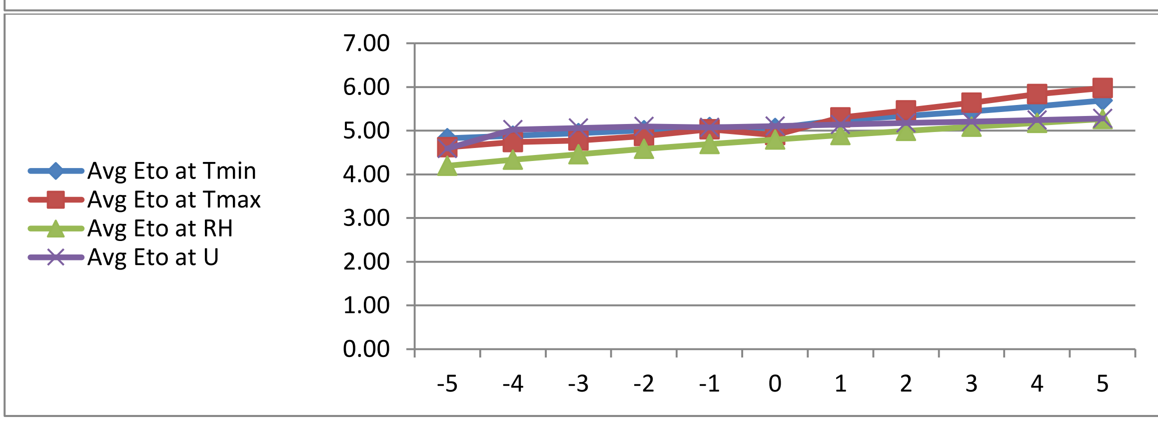
2.3 Estimation of Sensitivity Indices: Sensitivity analyses were conducted by increasing and decreasing an individual climate variable by one unit of increments up to five units (The value of each unit increment is 10% of the base value), while keeping the other variables constant [15] . The units used to express each climatic variable are: T max and T min (°C), RH (%) and U (km h−1). Using the climatic variables measured inside the greenhouse for each date ETo is calculated and considered as standard value for that date For each generated climate variable a new set of ETo values (on daily basis) was estimated. This was made for every three days to give data for ten days per month. Daily data was measured in April, August and November in each year for three houses per each study area (El Alafoon, Halfaya, and Shambat).The ETo average values for ten days in a month are taken to express the average set of ETo of that month. The yearly average values of ETo is considered as the average values of the three months of April, August and November in each year (2020, 2021 2022) in each house. Sensitivity of each monthly ETo generated from each climate variable using FAO 56-PM procedure was assessed using descriptive statistics (standard deviation - std, coefficient - CV%, and t-test), regression coefficient - r 2, slope and Christiansen uniformity of distribution (Ed) . [32]

RESULTS AND DISCUSSION

The study of the evaluation of performance is intended to uncover the response between changes in ETo to change in each climatic variable. A likely change in ETo is expected to change in climatic variables (Tmax, Tmin, Rs, RH avg, and U); however, it is important to analyze which variable has a significant effect on ETo estimation under different areas. The yearly sensitivity coefficient in ETo – mm- in terms of unit change with respect to unit change in each climate variable (Tmin, Tmax, RH, and U) is presented in Figs. 1-a,b,c Four separate lines are illustrated in each figure. The slope and intercept of change in ETo with respective change for each climate variable for the each year is shown in table 2, and are the averages of 3 years. However, it is important to analyze which variable has a significant effect on ETo estimation under different areas. Table 2 indicate that the regression coefficients between the changes in ETo relative to unit change in climate variables for each variable, ETo distribution uniformity with respective change in each climate input (Tmin, Tmax, RH, and U) , and level of sensitivity at 0.1,0.01, and 0.05 level of significance. The magnitude of the effect of a change in each climate variable on the change in ETo showed considerable variations among variables and sites (Fig. 1).

As given in table 2 the sensitivity of each climate variable to predict ETo was assessed using descriptive statistics (standard deviation - std, coefficient - CV%, and t-test), regression coefficient - r2, slope and Christiansen uniformity of distribution (Ed). The results showed that the change in (ETo) is linearly related to change in all climate variables (r2 = 0.94) except wind speed (U) (r2 = 0.46 to 0.68) at all years (Sohrabi et al, 1988). Further, According to relative dispersion (CV %), Std. and t-test ETo is significantly sensitive to (Tmax), (Tmin) followed by (RH) and least sensitive to (U) at all years (with the lowest slope of: 0.032 to 0.046). This result imply that determination of ETo inside greenhouse require more accuracy in determining T max, RH than T min and U2 which can be estimated with reduced precision. . [15] also reported the least effect of T min on ETo., based on the slope (Tmin slope is 0.081, to 0.103). In agreement with Estevez et al. (2009) and [19] the change in ETo was most sensitive (maximum slope) to Tmax and RH (Table2). This result of taking the slope as criteria of evaluation of sensitivity is used by Smajstrla et al. (1987). As shown in table 2 the low coefficient of variation obtained with changing of wind speed indicates its reduced impact on ETo and its less sensitivity (low R2 and low CV). In humid and sub-humid environment inside the greenhouse, and due to the high RH avg , the ETo demand is low. Under these conditions, the wind replaces the saturated air and removes heat energy. As a result, the effect of U on ETo in humid and sub-humid regions was less compared to dry conditions outside the greenhouse, where small variations in U may result in larger variations in the ETo rate [16,28]. The ETo is primarily affected by an increase in temperature due to higher capacity of air to hold water vapor, which transfers energy to the crop and exerts as such a controlling influence on the rate of ETo. The slopes of the regression line for T max were greater in Table 2 with a value of 0.131 to 0.148 which is greater than the values reported by Mohanpur (0.0786) in humid region and sub-humid region sites (Ludhiana: 0.0706), and Ranichauri: 0.0594).





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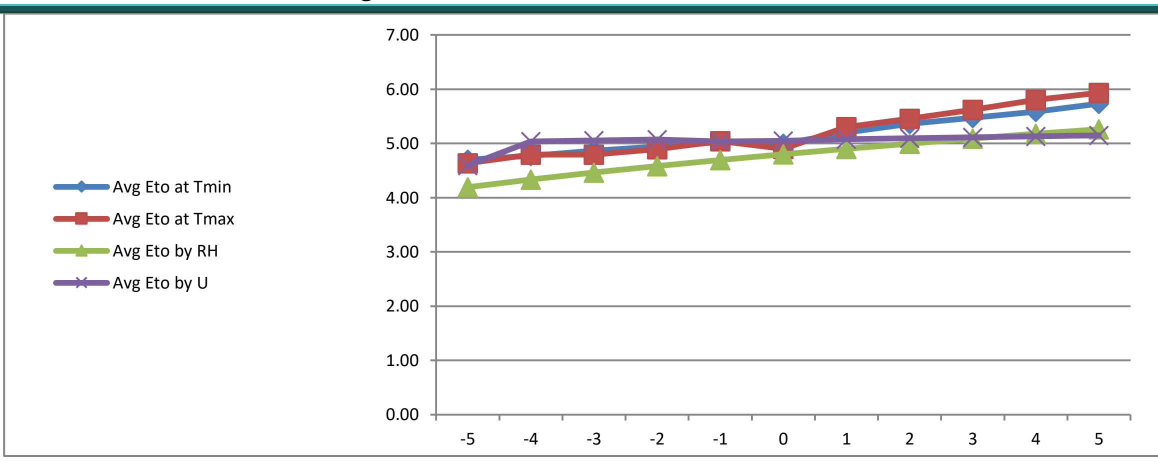

Figs. 1(*a,b,c*)*: Increase and decrease in ETo (mm) with respect to Increase and decrease in climatic variable for each study year: Tmax and Tmin = Max and min temperature (°C), U= wind speed (m/s), RH = relative humidity (%). Each variable was increased and decreased by one unit interval (10% of base value) up to five units.*

Table2: Sensitivity indices for evaluating impact of changing the climate variables on predicting ETo for three years

Replication	**Climate variable**	**Eto mm**	**R2**	**Slope**	**Ed %**	**Std dev**	**Coefficient of Variation CV %**	**Sensitivity Significance level**		
								0.1	***0.01***	***0.05***
Year one	***Tmin***	5.16	0.9714	0.0805	95.4	0.09	1.732	not Sensitive	Sensitive	not Sensitive
	Tmax	4.94	0.940	0.1476	91.1	0.269	5.091	Sensitive	Sensitive	Sensitive
	RH	4.8	0.9941	0.1059	93.6	0.129	2.704	Sensitive	Sensitive	Sensitive
	U	5.16	0.6796	0.0458	98.7	0.007	0.134	Sensitive	Sensitive	Sensitive
Year Two	***Tmin***	5.06	0.964	0.085	95.1	0.085	1.634	Sensitive	Sensitive	Sensitive
	Tmax	4.93	0.942	0.138	91.6	0.235	4.491	Sensitive	Sensitive	Sensitive
	RH	4.8	0.994	0.1059	93.6	0.129	1.36	Sensitive	Sensitive	Sensitive
	U	5.11	0.666	0.0453	98.6	0.011	0.119	Sensitive	Sensitive	Sensitive
Year Three	***Tmin***	4.99	0.967	0.103	94.1	0.123	2.383	Sensitive	Sensitive	Sensitive
	Tmax	4.93	0.9352	0.131	92	0.212	4.058	Sensitive	Sensitive	Sensitive
	RH	4.8	0.9994	0.106	93.6	0.129	2.704	Sensitive	Sensitive	Sensitive
	U	5.05	0.4615	0.031	99.4	0.002	0.032	Sensitive	Sensitive	Sensitive

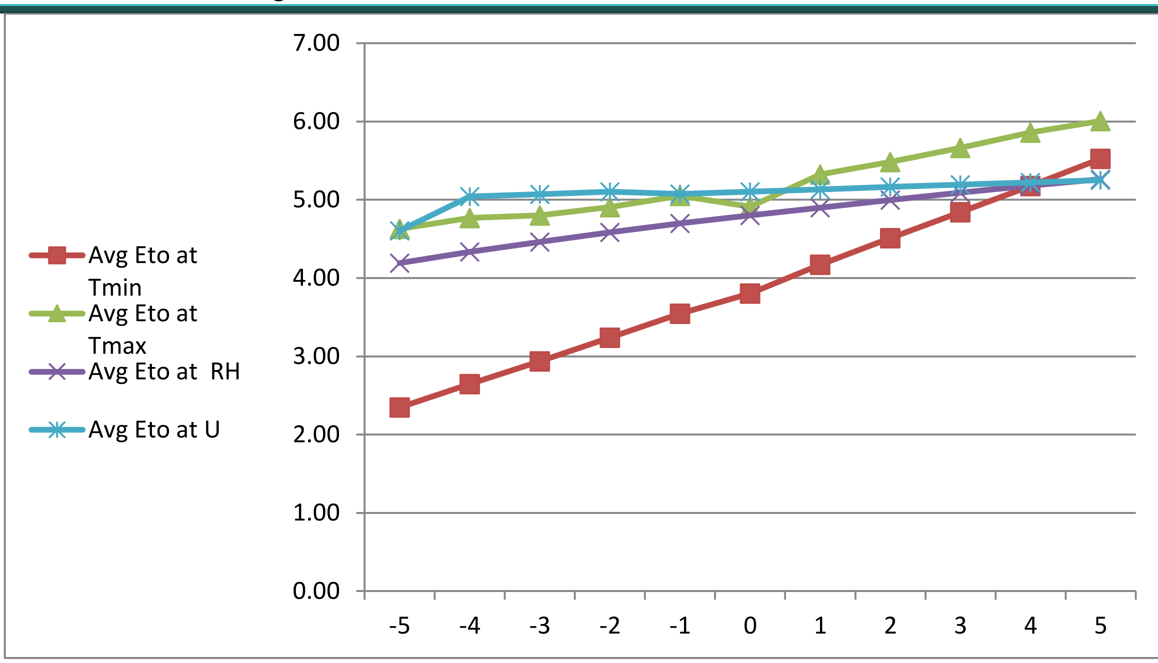

Figure 2: *Three year average variation of ETo due to increase and decrease of climate variables (Tmin. Tmax, RH,and U) at constant rate in the three sites*

Following [21] the impacts of changing (decreasing or increasing) climate elements on ETo can be visualized in figure 2. The figure illustrates that: For minimum temperature (Tmin): gradual increase or decrease in Tmin resulted on sharp linear increase or decrease in ETo, Changing Tmin resulted in lower values and mild effects on generated ETO values. For maximum temperature (Tmax): The positive change in Tmax produce positive effect on ETo while reduction of Tmax resulted on gradual reduced ETo. For relative humidity (RH): Incremental increase or decrease on RH induce gradual and flat change in ETo, Changes in RH values produced lower ETo than those values resulting from altering Tmax . For wind speed (U): The rate of increase of U results on decreasing Eto values , while decrease on RH results on decrease ETo.

CONCLUSIONS

The FAO-56 PM method is recommended as the standard method for estimating ETo, if all the required climatic data are available. In this study, the sensitivity of FAO-56 PM method was evaluated to change in climatic variables. The 3 years daily climatic data (Tmax, Tmin, RH, and U) were used as an input for the estimation of ETo by FAO-56 PM method and analyzing sensitivity in fan and pad greenhouses at three sites. The response of ET was linear, with high r2 values (0.94) in most cases, to changes in all climate variables, where ET was very insensitive to Tmin at all locations and seasons. Sensitivity of ETo to climate variables showed significant variations between various climate variables. Thereafter, Tmax was the most sensitive variables for most sites. ETo was less sensitive to U followed by T min at all sites The given results demonstrated that, in general, emphasis should be given to accurate measurements of, Tmax and RH, with less emphasis on U and Tmin since accurate estimate of radiation is directly associated with accurate measurement of relative humidity and air temperature. Results of this study should be useful for assessing the response of the standardized FAO56-PM equation in different climatic conditions.

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