CLIMATE PARAMETERS USED TO EVALUATE THE EVAPOTRANSPIRATION IN DELTA CENTRAL ZONE OF EGYPT

H. E. Gad [1] and S. M. El-Gayar [2]

[1] Mechanical Power Engineering Department, Faculty of Engineering,
Mansoura University, El-Mansoura 35516, Egypt
E-mail: he_gad@yahoo.com
[2] Senior researcher, Agriculture Engineering Research Institute, A. R. C,
Giza, P.O. 256, Egypt
E-mail: safelgyar@yahoo.com

ABSTRACT

The wrong water estimation for different crops is one of the main reasons for increasing the agriculture irrigation in Egypt. The Food and Agriculture Organization (FAO) Penman-Monteith equation is frequently used for calculating the reference evapotranspiration (ET_O) and hence the crops water requirements (ET). This equation contains many terms that depend on climate parameters such as the daily mean solar radiation, air temperature, relative humidity and wind speed. For more accurate results, it is essential to use accurate and suitable parameters for the Egyptian climate. For this reason, a MATrix LABoratory (MATLAB) computer program is constructed and used for computation and prediction of these parameters at the daily mean climate conditions of the river Nile Delta central zone of Egypt. Results obtained from alternative formulae used to estimate some of these parameters are compared. The data based on thermodynamic properties of the moist air (from steam tables data) and that obtained from the National Aeronautics and Space Administration (NASA) website are also used to derive alternative formula for this area. Results are shown as empirical equations and in graphical form to supply an accurate and quick tool for estimating the water requirements of different crops in this area.

Keywords: Climate parameters, evapotranspiration, Delta, Egypt

1. INTRODUCTION

Because of increasing the world's population, growing agricultural and industrial requirements, the world is on the brink of an unprecedented water crisis in the near future. Today, the irrigated agriculture requirements are estimated by about 70% of the total human fresh water resources available all over the world, FAO, Bruinsma [1]. The absence of appropriate irrigation management and wrong water estimation for different crops in Egypt are probably the main reasons of increasing the irrigated agriculture water use to about 85% of the total river Nile water share, 55.5 milliard m^3, (yearly agreement account Egypt and Soudan 1959), Ismail [2].

Water losses play an essential role in the crop irrigation management. Water losses from the plant-soil system occur mainly due to evaporation from soil, plant and that associated with sprinkler irrigation. The amount of evaporation in these three sources depends mostly on the amount of energy available for transformation of water from liquid to vapor form. This energy depends on four main factors; solar energy, air temperature, relative humidity and wind speed.

The irrigation requirement for any crop is the amount of water that must be applied to meet the crop's evapotranspiration (ET) needs. The amount of (ET) includes water that is needed for both evaporation and transpiration. Evaporation occurs from all wet surfaces, including soil, water and plants. Transpiration is the evaporation from plant through the leaves stomata. Both evaporation and transpiration occur in response to climate demand. Evapotranspiration is greatest on hot, sunny and dry days and lowest on cool, cloudy and humid days.

The water crisis is getting more worth in the Middle East territories, especially after increasing the agricultural and industrial development projects in this area. Thus, the available water resources have to be utilized in such a manner as to protect and conserve the available water reserves. In irrigated agriculture, this is obtained through the effective management of water consumption. Therefore, the irrigation systems must apply water in the most efficient way possible to prevent unnecessary losses and water wastage. Accurate calculations of water requirements for different crops have also critical influence.

Most of the available data depend on the FAO Penman-Monteith equation for calculating the reference evapotranspiration (ET_O) which is referred to the green grass as a reference crop. In arid or semi-arid areas, alfalfa is more suitable as a reference crop because of its deep root system, which reduces its susceptibility to water stress resulting from dry weather. However, all terms in this equation are related to the climate parameters, especially the daily mean global solar radiation, air temperature and wind speed. In some cases, there is more than one formula used to calculate the same parameter of the Penman-Monteith equation. In this paper, all the available alternative formulae for these parameters are considered.

Several successful attempts for estimating and improving the Penman-Monteith equation parameters are reported. The latent heat of vaporization is given as a linear function with air temperature by Harrison [3]. A correlation equation for the slope of saturation vapor pressure curve is reported by Murray [4]. An alternative formula for this parameter is used by Richard et al. [5]. Three different empirical equations for calculating the saturation vapor pressure in terms of air temperature are reported by Allen et al [6], Andy and Stanley [7] and Yaws and Yang [8]. Although these equations have different algorithms, close results are obtained from them. It is to be noted that most of these correlations are restricted within the temperature range from 0 to 50 °C.

On the other hand, global solar radiation strongly controls the evaporation from the plants and soil surface. Small uncertainties in solar radiation may have considerable effect on the calculated value of ET_O, Llasat and Snyder [9]. Solar radiation is usually measured by pyranometers, which are in any case expensive and fragile devices. Solar radiation data are almost not readily available from national observatories, especially in Egypt. These data depend mainly on the latitude and geographical situation of the concerned area. Therefore, several solar irradiation correlations for many places worldwide are available in the literature. In this work, the most frequently used of these correlations are considered, Meinel and Mainel [10], Duffie and Beckman [11] and Hinrichsen [12]. Graphical comparison of results obtained from these correlations is carried out.

The aim of this research work is to help the decision maker to decide and use the most suitable formulae for the river Nile Delta central zone of Egypt. Most of the Egyptian agriculture activities are concentrated in this area. The results of different alternative formulae for the same parameter are graphically compared with that obtained using thermodynamic properties of the moist air (from steam tables data) and that from the National Aeronautics and Space Administration (NASA) website at the latitude and longitude of river Nile Delta central zone of Egypt (around 31^{o}N and 31^{o} E). The final target of this research work is to increase the accuracy of (ET_O) and (ET) estimation under this area climate conditions. A great benefit will be also reached when the soil water balance modeling is considered.

2. MATERIALS AND METHOD

The Food and Agriculture Organization (FAO) of the United Nations has been proposed the famous and well known Penman-Monteith equation, Allen et al. [6], as the most adequate method of calculating the reference evapotranspiration (ET_O). The crop water requirements which is equal to the evapotranspiration (ET) for any crop can be calculated from the equation ($ET = k_C \times ET_O$), where the value of the crop coefficient (k_C) is known for different crops at different growing stages.

The most frequently used method employed to evaluate any crop ET uses the Penman-Monteith equation for calculating the value of (ET_O). Associated correlations for predicting solar radiation, evaporation from bare soil associated with crop transpiration are based on a water balance of the soil surface layer.

The reference evapotranspiration (ET_O) is given in (mm/day) from the Penman-Monteith equation as,

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

Where, R_n is the net solar radiation at the crop surface (MJ/m^2 day),

G soil heat flux density (MJ/m^2 day),
T mean daily air temperature at 2 m height (°C),
U_2 wind speed at 2 m height (m/s),
e_s saturated air vapor pressure (kPa),
e_a vapor pressure of the actual air (kPa),
Δ slope of saturated air vapor pressure curve (kPa/°C), and
γ is the psychrometric constant (kPa/°C).

It is clear that Penman-Monteith equation (1) uses the standard climatological records of the daily mean solar radiation, air temperature, humidity and wind speed. To ensure the integrity of computations, the weather measurements should be made at 2 m (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water.

The methodology of this work is carried out by a MATLAB computer program that constructed and used for the evaluation of the Penman-Monteith equation parameters at the daily mean climatic data of the Nile Delta central zone of Egypt. These parameters are the daily mean solar radiation at the crop surface from which the net solar radiation at the crop surface (R_n) and the soil heat flux density (G) are estimated, wind speed at 2 m height (U_2), saturated air vapor pressure (e_s), vapor pressure of the actual air (e_a), slope of saturated air vapor pressure curve (Δ) and the psychrometric constant (γ).

However, some of these parameters namely; γ, Δ and e_s are directly related to the thermodynamic properties of water vapor in the air which in turn are related to the air temperature (T). Other climatic variables such as (RH and T_{dew}) are used to calculate the value of (e_a). Therefore, the input to this part of the program is restricted to the mean daily values of T, RH and T_{dew}. A plot of γ, Δ and e_s can be obtained as a function of temperature.

The other part of these parameters such as (T, U_2, R_n and G) is directly or indirectly related to global solar radiation. The daily mean solar radiation data on the horizontal earth's surface and air temperature can be measured or collected from climatological records of any nearby observatory or from the NASA website. Measurements may require expensive and hardly available devices. Otherwise, solar radiation data and air temperature can be calculated from imperial equations. The input fixed data for this part of program is the geographical situation of the place such as; height, latitude and longitude. The variable input data are only the time of the day and the number of day in the year.

For more precise and accurate results, these parameters should be calculated from correct correlations as possible. The problem is that some of these parameters (and variables used in their evaluation) have more than one alternative formula used for calculating their value such as:

1- Psychrometric constant (γ),
2- Latent heat of evaporation (λ),

3- Slope of saturated air vapor pressure curve (Δ),
4- Saturated air vapor pressure (e_s),
5- Solar radiation.

Graphical comparison of results obtained from alternative formulae will be useful in approaching and deriving more accurate correlations.

However, the land of the river Nile Delta zone of Egypt is almost plain and flat with few meters above the sea level. The MATLAB computer program is capable of calculating the hourly solar radiation intensity on a horizontal surface at any given day of the year using any given mathematical model. The program has also the facility to numerically integrate the hourly values to obtain the corresponding daily solar radiation. A small time step as 0.01 h is employed in calculations to obtain accurate results that can be represented in graphical form or as best fit correlations in terms of the day number starting from January first, (J). In this work, the values of the Penman-Monteith equation parameters are the only of concern. The value of reference evapotranspiration (ET_O) is not taken into consideration.

3. RESULTS AND DISCUSSION

Psychrometric Constant

The psychrometric constant, γ is given by,

$$\gamma = \frac{C_p P}{\varepsilon \lambda} \tag{2}$$

Where, P is the atmospheric pressure = 101.3 (kPa)
C_p specific heat at constant pressure = 1.005 (KJ/kg °C),
ε ratio between molecular weight of water vapor/dry air = 0.622, and
λ is the latent heat of vaporization (MJ/kg)

The latent heat of vaporization (λ) is given as a function of air temperature by Harrison [3] as,

$$\lambda = 2.51 - 2.361 \times 10^{-3}\ T \tag{3}$$

Figure 1 shows the variation of (λ) with temperature as obtained from equation (3). The data collected from many steam tables from different sources, in the temperature range (0 – 50 °C) are averaged, Gad [13], and also plotted in the same figure. It is clear that the steam tables data are close to that represented by equation (3) especially at the middle of temperature range.

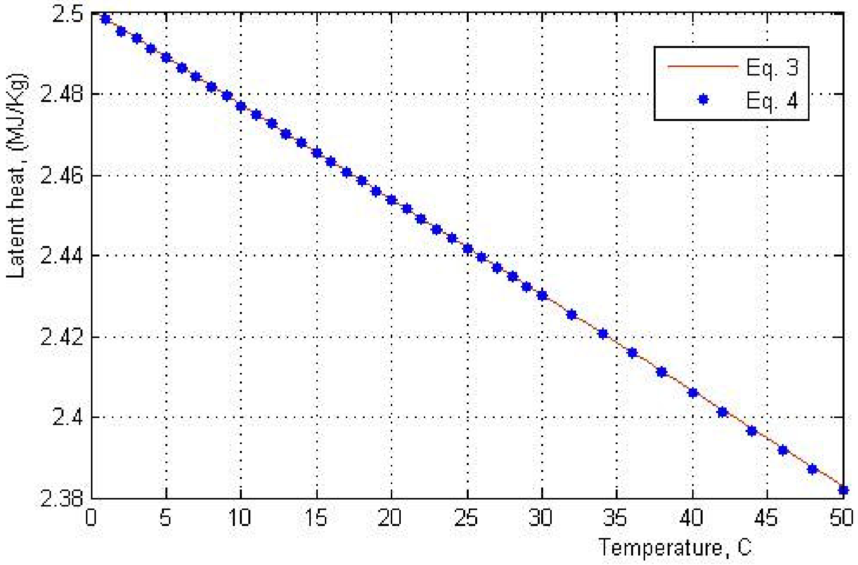

Fig. 1. Variation of latent heat of vaporization with temperature

An exact best fit equation can be obtained for the plot of steam tables data using the MATLAB and represented by,

$$\lambda = 2.501 - 2.3664 \times 10^{-3}\ T \tag{4}$$

This formula is seen to be very close to equation (3), but yields more accurate results. Substituting equations (3) and (4) in (2), the psychrometric constant can be written respectively as,

$$\gamma = 1/(15.33517 - 0.014425\ \ T) \tag{5}$$

and $$\gamma = 1/(15.2802 - 0.014458\ \ T) \tag{6}$$

Figure 2 shows the variation of the psychrometric constant (γ) with air temperature (T) as obtained from equations (5) and (6). It is clear that the results obtained from equation (6) are higher than that obtained from equation (5) by about 0.004 kPa/°C. This difference is expected since (λ) is in the dominator of equation (2).

However, for more accurate results, equations (4) and (6) can be used to calculate (λ) and (γ) respectively since the results from these equations fit exactly with that obtained with steam tables.

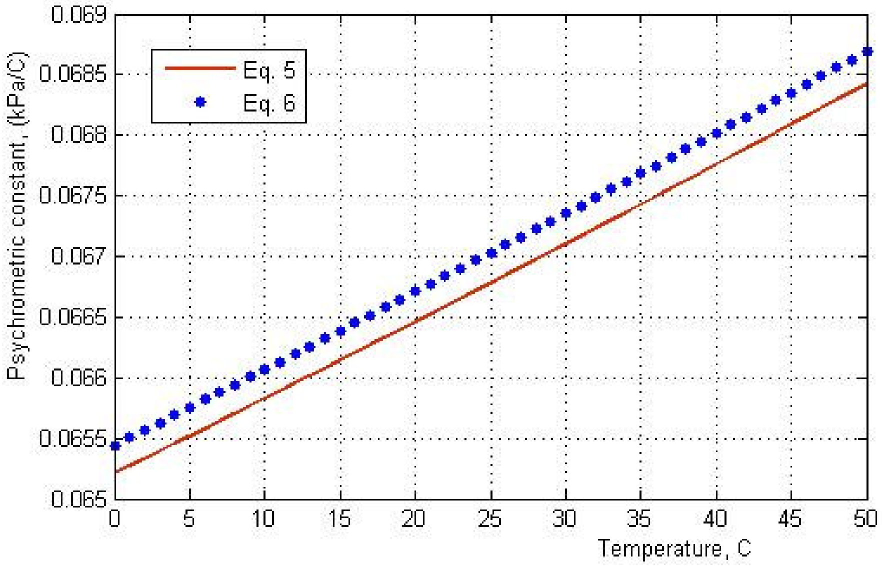

Fig. 2. Variation of the psychrometric constant with air temperature

Slope of Saturation Vapor Pressure Curve

The slope of saturation vapor pressure curve (Δ, kPa/°C) can also be obtained in terms of air temperature (T, °C) as given by Murray [4] in the following formula,

$$\Delta = \frac{4098\left[0.6108\ \exp\left(\frac{17.27\ T}{T+237.3}\right)\right]}{(237.3\ + T)^2} \tag{7}$$

An alternative formula is used by Richard et al. [5] as,

$$\Delta = 0.2(0.00738T + 0.8072)^7 - 0.000116 \tag{8}$$

The steam tables data for the same temperature range (0 to 50 °C) are fed to the MATLAB program and yields the following best fit correlation,

$$\Delta = 0.00021501\, T^2 - 0.00025132\, T + 0.061309 \tag{9}$$

A comparison between the values of (Δ) obtained from the above three equations is shown in Fig. 3. Results of equations (7) and (8) are close to that obtained from steam tables especially in the middle of the temperature range (from 7 to 43 °C). The difference increases as the temperature approaches the limits of the temperature range as shown in the figure.

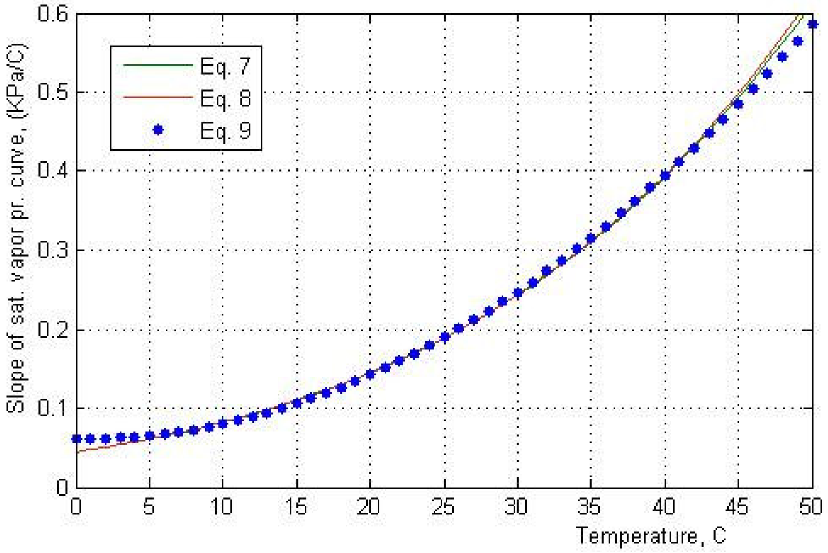

Fig. 3. Variation of the slope of saturation vapor pressure with air temperature

The Saturation Vapor Pressure

The saturation vapor pressure (e_s, kPa) is also related to air temperature (T, °C), and can be obtained from the relationship expressed by Allen et al [6] as,

$$e_s = 0.6108\ \exp\left(\frac{17.27\ T}{T + 237.3}\right) \tag{10}$$

An alternative formula is given by Andy and Stanley [7] as follows,

$$e_s = \exp\left(\frac{16.78\,T - 116.9}{T + 273.3}\right) \tag{11}$$

A different relationship between e_s and T (August equation) is also reported by Yaws and Yang [8] as,

$$e_s = \left(\frac{10}{76}\right) \times 10^{8.07131\ -\ \left(\frac{1730.63}{233.426 + T}\right)} \tag{12}$$

Results based on steam tables data using the MATLAB program yields the following equation,

$$e_s = 7.167 \times 10^{-5}\ T^3 + 7.167 \times 10^{-4}\ T^2 + 0.061309\ T + 0.57075 \tag{13}$$

A comparison of results obtained from the above equations (10), (11) and (12) and that obtained from steam tables data equation (13) is presented in Fig. 4. Results from equations (10) and (11) reveals a perfect fit with that of steam tables, while that obtained from equation (12) show a little deviation especially at higher temperature. This deviation increases with temperature as shown in the figure. However, the closeness of results is a proof of validation of the derived correlations.

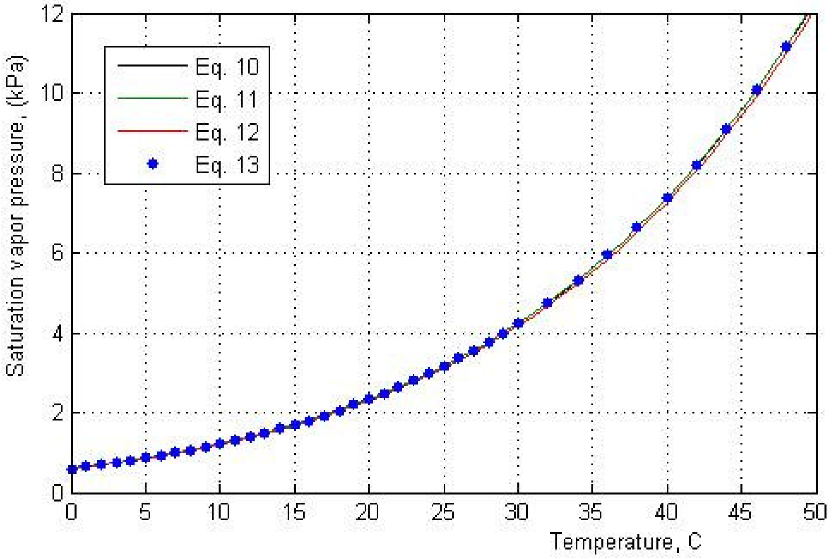

Fig. 4. Variation of saturation vapor pressure with air temperature

The Actual Vapor Pressure

The relative humidity (RH %) expresses the degree of saturation of air and is defined as the ratio of actual vapor pressure in the air (e_a) to that of saturated air (e_s) at the same temperature. Therefore, (e_a) can be calculated from,

$$e_a = e_s \left(\frac{RH}{100}\right) \tag{14}$$

The relative humidity can be measured or obtained from any nearby observatory. If not possible, it can be obtained from NASA website. However, its average value in the Nile Delta central zone ranges from 58.4 to 63.36% as obtained from NASA website averaged over 10 years as shown in Table (1).

Table (1) Relative humidity and dew point temperature, NASA

Year 1995-2005	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RH%	61.51	62.24	61.84	58.40	60.26	61.79	59.60	61.48	61.72	63.95	63.36	60.46
T_{dew}, °C	7.11	6.95	8.03	9.54	12.78	16.24	18.08	18.95	17.75	15.67	12.39	8.56

The average monthly values of the dew point temperature (T_{dew} °C) over 10 years are also given in Table (1) at the river Nile Delta central zone. Thus, the actual vapor pressure (e_a, kPa) in the atmospheric air can be determined from equation (11) at the dew point temperature as follows:

$$e_a = 0.6108 \exp\left[\frac{17.27\ T_{dew}}{T_{dew} + 237.3}\right] \tag{15}$$

The dew point temperature (T_{dew}, °C) can also be calculated from the formula given by Murray [4] as,

$$T_{dew} = 237.3\left[\frac{1}{\dfrac{\mathrm{Ln}(RH/100)}{17.27} + \dfrac{T}{237.3 + T}} - 1\right]^{-1} \tag{16}$$

The average monthly values of RH% and (T) over 10 years in the Nile Delta central zone are obtained from NASA website and shown in Table (1) and (2) respectively. These values are used in equation (16) for the calculation of (T_{dew}). Figure 5 shows a plot of (T_{dew}) as obtained from equation (16) and that obtained from NASA website. A reasonable agreement between the two values is observed.

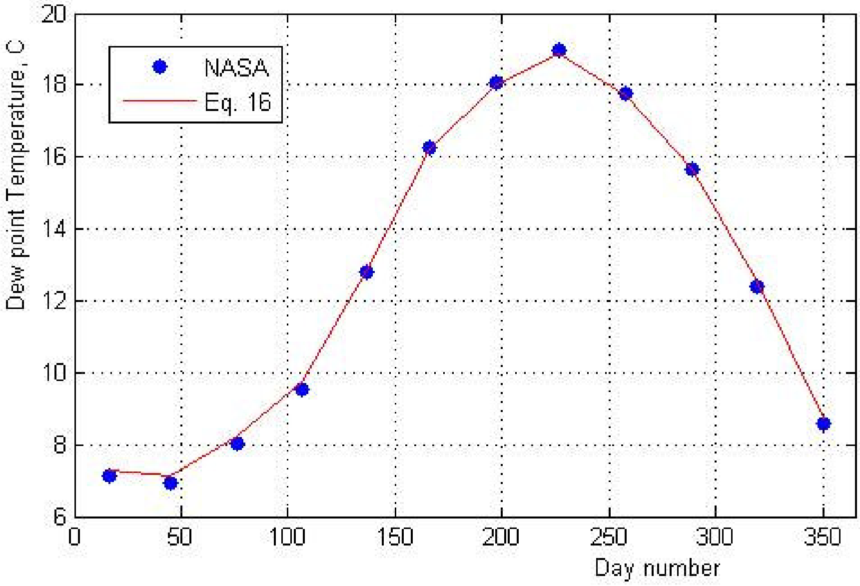

Fig. 5. Variation of T_{dew} in the Nile Delta central of Egypt

It is to be noted that the term (e_s-e_a) in equation (1) is known as the (vapor pressure deficit). It is the difference between the vapor pressure of saturated air (e_s) and that of the actual air. The vapor pressure deficit can be calculated using equations (13), (15) and (16).

Air Temperature

Table (2) shows the minimum (T_{min}), maximum (T_{max}) and average (T) air temperature (10 m above the earth) as obtained from NASA website over the Nile Delta central zone of Egypt. These data are taken as monthly average over 10 years. Conversion formulae of the data to the height of 2 m above the earth's surface are available in the literature, Allen et al. [6].

Figure 6 shows a plot of these data over the year. The average daily air temperature is measured in the meteorological station on the roof of the agriculture engineering department (Mansoura University at latitude of 31.045° N and longitude of 31.365° E) and plotted on the same figure. These measured data are recorded only in 2008. However, a small difference of about -1.6 to 1.8 °C can be observed.

Table (2) Minimum, maximum and average air temperature, NASA

Year 1995-2005	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{min}, °C	11.83	11.10	12.09	14.31	17.29	20.81	23.33	24.08	23.05	20.56	17.29	13.78
T_{max}, °C	17.78	17.64	19.20	21.94	24.73	27.72	30.51	30.50	28.72	25.52	22.40	19.29
T, °C	14.58	14.24	15.49	18.02	20.82	23.99	26.54	26.92	25.62	22.86	19.69	16.38

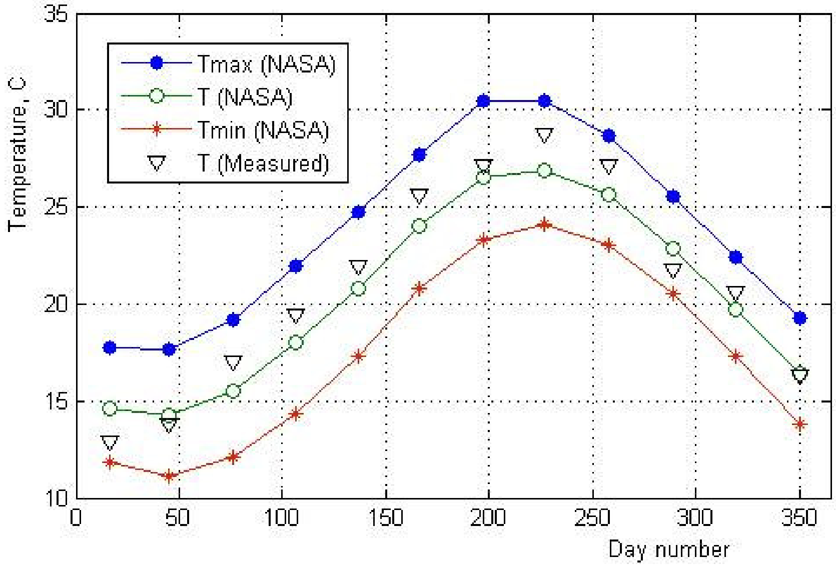

Fig. 6. Variation of T_{max}, T, and T_{min} in the Nile Delta central of Egypt

Wind Speed

The 10-years average wind speed (m/s) at a height of 10 m collected from NASA website is shown in Table (3). To adjust wind speed data to a 2 m height, a logarithmic wind speed profile given by Allen et al. [6] may be used as,

$$U_2 = U_z \frac{4.87}{\mathrm{Ln}(678\ z - 5.42)} \tag{17}$$

Where, U_2 and U_z is the wind speed at 2 m above ground surface and at z m above ground surface (m/s) respectively.

Table (3) Monthly averaged wind speed at 10 m above earth's surface, NASA

Year 1995-2005	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind speed (m/s)	4.80	5.08	4.88	4.44	4.30	4.19	4.29	4.36	4.42	4.43	4.28	4.69

Solar Radiation

Solar radiation data is essential for estimating the ET_O value. Neglecting the reflection component, the hourly global solar radiation intensity on a horizontal surface, $\overline{R}_h$ in clear sky model is given by Meinel and Mainel [10] as,

$$\overline{R}_h = \overline{R}_a \left(0.7\right)^{m^{0.678}} \tag{18}$$

Where, $\overline{R}_a$ is the extraterrestrial irradiance on a horizontal surface given by Markvart and Kreider [14] as,

$$\overline{R}_a = R_{sc}\left[1 + 0.033\cos\left(\frac{2\pi J}{365}\right)\right](\cos L \cos\delta \cos h + \sin L \sin\delta) \tag{19}$$

Where, R_{sc} is the solar constant = 1.367 kJ/m^2.s
and, m is the air mass ratio calculated for clear sky condition by Kreith and Kreider [15] as,

$$m = \left[1229 + (614\sin\alpha)^2\right]^{0.5} - 614\sin\alpha \tag{20}$$

Where, α is the sun altitude angle obtained from,

$$\sin\alpha = \cos L \cos\delta \cos h + \sin L \sin\delta \tag{21}$$

L is the latitude angle of the place,
h solar hour angle defined by $h = (12 - t) \times 15^{o}$ (t is the local time, h), and

δ is the solar declination angle defined by,

$$\delta = 23.5 \ \sin\left[\frac{360}{365}(J + 284)\right] \tag{22}$$

Where, J is the day number starting from January first.

The hourly global solar radiation intensity on a horizontal surface, R_h can also be obtained from Duffie and Beckman [11] as,

$$\overline{R}_h = k_t \, \overline{R}_a \tag{23}$$

Where, k_t is the averaged clear sky clearness index. The value of k_t can be measured in site or obtained as a monthly averaged value from NASA website. Table (4) shows the monthly averaged value of k_t in river Nile Delta from 1995 to 2005. The value of k_t can be obtained as a function of (J) from the best fit using the MATLAB program as,

Table (4) Monthly averaged clear sky clearness index (Latitude 31 N, longitude 31°) from NASA

Year 1995-2005	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
k_t	0.68	0.67	0.70	0.71	0.71	0.71	0.69	0.70	0.69	0.67	0.66	0.65

These values are correlated by the MATLAB program as,

$$k_t = -1.6\times10^{-6} J^2 + 0.0004943 J + 0.66732 \tag{24}$$

The daily extraterrestrial solar radiation on a horizontal surface, R_a can be obtained from Iqbal [16] as,

$$R_a = \frac{24}{\pi} R_{sc}\left[1 + 0.033\cos\left(\frac{2\pi J}{365}\right)\right](h_s \sin L \sin\delta + \cos\delta \cos L \sin h_s) \tag{25}$$

Where h_s is the sunset hour angle obtained from Duffie and Beckman [11] as,

$$h_s = \cos^{-1}(-\tan L \tan\delta) \tag{26}$$

An alternative correlation is frequently used to estimate the solar radiation falling on the horizontal crop surface namely the Angstrom formula, Hinrichsen [12] as,

$$\overline{R}_h = \left[a + b\left(\frac{n}{N}\right)\right]\overline{R}_a \tag{27}$$

Where (a) is a regression constant, expressing the fraction of extraterrestrial solar radiation reaching the earth on overcast days (n = 0) and (n/N) is the ratio of the actual duration of sunshine, n to the maximum possible duration of sunshine or daylight hours N. For clear sky (n=N) at sea level, and (a+b=0.75). As an example, Fig. 7 shows the hourly solar radiation on a horizontal surface on March, 21 at Latitude of L=31° N. Similar data measured in the agriculture engineering department (Mansoura University) are plotted on the same figure.

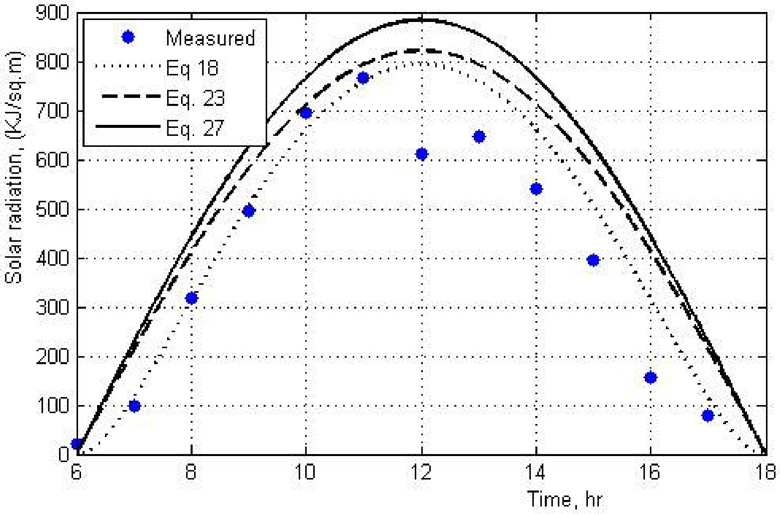

Fig. 7. Hourly solar radiation on a horizontal surface at March, 21 (L=31° N).

However, the hourly variation of solar radiation is seldom used in estimating the (ET) and (ET_o) values. The global daily solar radiation is usually used instead. The daily solar radiation on the earth's surface (MJ/m^2) can be obtained by integrating equations (18), (23) or (27) each day of the year. The integration is performed numerically by the MATLAB program and the results are shown in Fig. 8. The extraterrestrial solar radiation on horizontal surface (R_a) is also obtained from equation (25) and shown in Fig. 8. On the other hand, similar data for the same area around (Latitude 31° N and longitude 31°) are collected from NASA website as averaged over 10 years as shown in Table (5). The data from NASA website are also plotted on the same figure. Comparing results from different sources, it is clear that the difference between results is considerable as shown in Fig. 8.

Table (5) Monthly averaged insolation on a horizontal surface (MJ/m^2/day), NASA

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995 – 2005	11.23	13.82	18.72	22.86	26.82	29.05	27.68	25.52	22	16.56	12.38	9.94

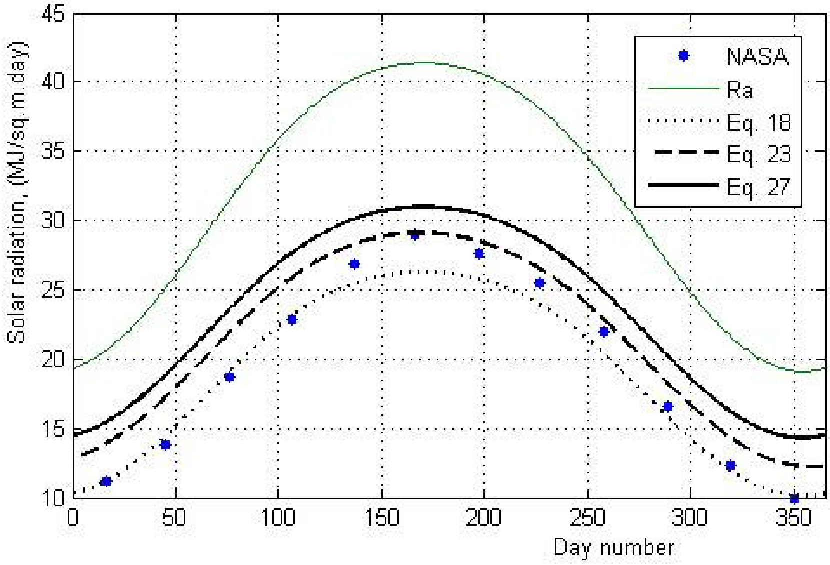

Fig. 8. Solar radiation on earth's surface at (Latitude 31° N and longitude 31°)

However, equation (23) is seen to be more suitable in summer season crops and (27) is more suitable otherwise to calculate the daily mean solar radiation on the earth's surface in the river Nile Delta central zone of Egypt according to the closeness of these data to that from NASA.

Referring to equation (1), the net radiation R_n (MJ/m^2day) is given by,

$$R_n = R_{ns} - R_{nl} \tag{28}$$

Where, R_{ns} (MJ/m^2day) is the net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - a')R_h \tag{29}$$

R_{nl} is the net outgoing long wave radiation (MJ/m^2day) expressed quantitatively by the Stefan-Boltzmann law as,

$$R_{nl} = \sigma\left[\frac{(T_{max} + 273)^4 + (T_{min} + 273)^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_h}{R_{hc}} - 0.35\right) \tag{30}$$

Where, (a) is the albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop, and σ is the Stefan-Boltzmann constant (4.903 10^{-9} MJ/ K.m.day). For clear sky condition, R_h = that of actual cloudy (R_{hc}). Results of equation (28) using equations (18), (23) and (27) are shown in Fig. 9. These results are obtained with the help of (29) and (30) for calculation of (R_{ns}) and (R_{nl}) respectively. The value of (e_a) as obtained from equation (15) uses the data of (T_{dew}) and (RH) from Table (1). All these data are fed to the MATLAB program for calculation of the net radiation (R_n).

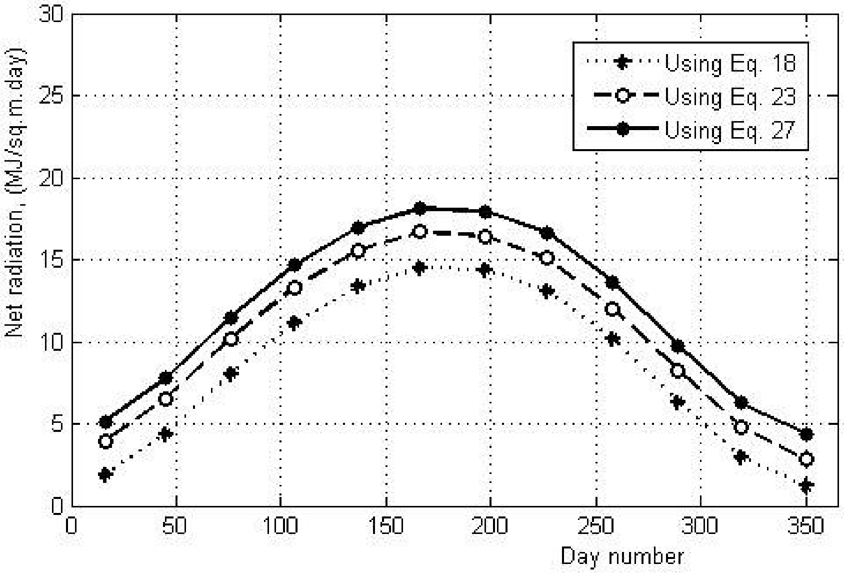

Fig. 9. Net radiation on earth's surface at (Latitude 31^o N and longitude 31^o)

Soil Heat Flux

Complex models are available to describe soil heat flux (G) such as that proposed by Allen et al. [6], based on the idea that the soil temperature follows air temperature. However, more impeller formula for Soil heat flux G (MJ/m^2 day) can be estimated from the net solar radiation is suggested by Su et al. [17] as,

$$G = R_n\left[b_c + (1 - f)(b_s - b_c)\right] \tag{31}$$

Where, f is the fractional vegetation cover, ranging from 0 to 1. b_c and b_s are empirical coefficient: $b_s = 0.315$, Kustas and Daughtry [18] and $b_c = 0.05$, Monteith [19].

Because soil heat flux is small compared to R_n, particularly when the surface is covered by vegetation and calculation time steps are 24 hours or longer, a simple procedure is presented here:

For one day and ten-day periods:

As the magnitude of the day or ten-day soil heat flux beneath the grass reference surface is relatively small, it may be ignored and thus:

$$G_{day} \approx 0 \tag{32}$$

For hourly or shorter periods:

For hourly (or shorter) calculations, G beneath a dense cover of grass does not correlate well with air temperature. Hourly value of G can be approximated during daylight periods as:

$$G_{hr} = 0.1\ R_n \tag{33}$$

and during nighttime periods as:

$$G_{hr} = 0.5\ R_n \tag{34}$$

Where the soil is warming, the soil heat flux G is positive. The amount of energy required for this process is subtracted from R_n when estimating (ET_O) and (ET).

4. CONCLUSIONS

The FAO Penman-Monteith equation contains many terms that depend on climate parameters such as the daily mean solar radiation, air temperature, relative humidity, psychrometric constant, vapor pressure, slope of saturated air vapor pressure curve and wind speed. There are more than alternative formulae to calculate some of these parameters. To obtain better accurate results of (ET_O) and suitable for the Nile Delta central zone of Egypt, these terms and parameters should be accurate. The aim of this study is to decide the most accurate and suitable formulae for this area. Therefore, a MATLAB computer program is constructed for the computation of these parameters at the daily mean air temperature and solar radiation of this area for a temperature range from 0 to 50 °C. Comparison of results obtained from alternative formulae is carried out. The data based on the thermodynamic properties of moist air from the steam tables and that obtained also from NASA website are used to decide the best suitable formula for this area. Results are shown in graphical form and best fit equations, and can be concluded as follows:

1. More accurate results, equations (4) and (6) can be used to calculate (λ) and (γ) respectively since the results from these equations fit exactly with that based on the moist air thermodynamic properties obtained from the steam tables.
2. Results of (Δ) from equations (7) and (8) are close to that obtained from steam tables equation (9) especially in the temperature range (from 7 to 43 °C).
3. Results of (e_s) from equations (10) and (11) reveals a perfect fit with that of steam tables equation (13), while that obtained from equation (12) show a little deviation especially at higher temperature.
4. Reasonable difference of solar radiation results obtained from alternative formulae is observed. Equation (23) is more suitable to calculate the daily mean solar radiation on the earth's surface (R_h) in summer season crops and equation (27) is more suitable otherwise. Results for net radiation (R_n) and presented graphically using these equations.
5. Results of other parameters such as the daily mean relative humidity (RH), air temperatures (T_{max}, T and T_{min}), dew point temperature (T_{dew}), wind speed (U_2) and soil heat flux (G) are presented in correlated equations, tables or in graphical form.

6. These results represent an accurate and quick tool for estimation of the reference evapotranspiration (ET_O) and water requirements (ET) of different crops in the Nile Delta central zone of Egypt.
7. For future study, it is recommended to investigate the influence of these parameters especially solar radiation data obtained from different sources on the reference evapotranspiration.

ACKNOWLEDGEMENT

The authors wish to thank professor Abdellatif, S. M., Meteorological station, Agriculture Engineering Department (Mansoura University) for providing the solar radiation and air temperature data.

5. NOMENCLATURE

a, b	Regression constants,
b_c, b_s	Empirical coefficient,
C_p	Specific heat of air at constant pressure=1.005 (KJ/kg °C),
e_a	Actual vapor pressure (kPa),
e_s	Saturation vapor pressure (kPa),
$e_s – e_a$	Saturation vapor pressure deficit (kPa),
ET	Crop evapotranspiration under standard conditions (mm/day),
ET_O	Reference crop evapotranspiration (mm/day),
f	The fractional vegetation cover,
h	Solar hour angle (rad),
h_s	Sunset hour angle (rad),
G	The soil heat flux density (MJ/m^2 day),
J	The day number starting from January first,
k_C	crop coefficient,
k_t	Monthly averaged clear sky clearness index,
L	Latitude angle of the place (deg, rad),
m	Air mass ratio,
n/N	The ratio of the actual duration of sunshine,
P	The atmospheric pressure=101.3 (kPa),
R_a	Extraterrestrial daily solar radiation on a horizontal surface (MJ/m^2.day),
RH	Relative humidity (%),
R_h	Solar radiation on a horizontal surface (clear sky) (MJ/m^2 day),
R_{hc}	Solar radiation on a horizontal surface (actual cloudy) (MJ/m^2 day),
R_n	Net solar radiation at the crop surface (MJ/m^2 day),
R_{nl}	Net outgoing long wave radiation (MJ/m^2 day),
R_{ns}	Net short wave radiation resulting from the balance between incoming and reflected solar radiation (MJ/m^2 day),
R_{sc}	The solar constant = 1367 (W/m^2.s),
t	The local time (hr),

T	The mean daily air temperature at 2 m height (°C),
T_{dew}	The dew point temperature (°C),
T_{max}	The maximum air temperature (°C),
T_{min}	The minimum air temperature (°C),
U_2	Wind speed at 2 m above ground surface (m/s),
U_z	Wind speed at z m above ground surface (m/s).

Greek symbols

α	Sun altitude angle
δ	Solar declination angle
Δ	Slope of vapor pressure curve (kPa/°C)
γ	Psychrometric constant (kPa/°C)
λ	Latent heat of vaporization (MJ/kg)
ε	Ratio between molecular weight of water vapor/dry air = 0.622
σ	The Stefan-Boltzmann constant ($4.903\ 10^{-9}$ MJ/ K^4m^2day).

REFERENCES

[1] FAO, Bruinsma, J., “World Agriculture: Towards 2015/2030”, *A FAO Perspective. Earthscan Publications Ltd.*, London, 2003.

[2] Ismail, S. M., "Design and Management of Field Irrigation Systems", pp. 5-188 *Elmarefa, Alex*, 2002.

[3] Harrison, L. P., “Fundamental’s concepts and definitions relating to humidity”, *In Wexler, A* (*Editor*) *Humidity and moisture*, Vol. 3, Reinhold Publishing Co., New York, 1963.

[4] Murray, F. W., “On the computation of saturation vapor pressure”, J. Appl. Meteor. 6: 203-204, 1967.

[5] Richard, G. A., Luis, S. P., Dirk, R. and Marten, S., “Crop evapotranspiration - Guidelines for computing crop water requirements", *FAO Irrigation and Drainage paper 56*, 1998.

[6] Allen, R.G., Pereira, L.S., Raes, D., and Smith, M, “Crop evapotranspiration: Guidelines for computing crop requirements”, *Food and Agriculture Organization* (*FAO*), Rome, Italy, 1998.

[7] Andy D. Ward and Trimble, S.W., “Environmental Hydrology”, *Second Edition, Lewis Publishers*, 2004.

[8] Yaws, C.L. and Yang, H.C., "To estimate vapor pressure easily", *Hydrocarbon Processing*, October, 1989.

[9] Llasat, M.C. and Snyder, R.L., “Data error effects on net radiation and evapotranspiration estimation”, *Agricultural and Forest Meteorology*, 91(3/4): 209-221, 1998.

[10] Meinel, A. and Mainel, M., “Applied Solar Energy, An Introduction”, *Addison-Wesley*, Reading, MA, 1976.

[11] Duffie J.A. and Beckman, W.A., “Solar engineering of thermal processes”, *John Wiley and Sons Inc*, New York, 1991.

[12] Hinrichsen, K., “The Angstrom formula with coefficients having a physical meaning”, *Solar Energy*, 52 (6), pp. 491-495, 1994.

[13] Prepared by Gad, H.E., "Steam tables", ISBN 977-19-7848-9, Third edition, *Mansoura University*, 2006.

[14] Markvart, T., and Kreider, Ed., “Solar Electricity”, *John Wiley & Sons, Chichester*, U.K, 1994.

[15] Kreith, F. and Kreider, J.F., “Principles of solar engineering”, *McGraw-Hill*, New York, 1994.

[16] Iqbal M., “An Introduction to Solar Radiation”, *Academic Press*, Ontario, 1983.

[17] Su, Z., Schmugge, T., Kustas, W.P. and Massman, W.J., “An evaluation of two models for estimation of the roughness height for heat transfer between the land surface and the atmosphere”, *Journal of Applied Meteorology*, 40 (11), pp. 1922-1951, 2001.

[18] Kustas, W.P. and Daughtry, C.S.T, “Estimation of the soil heat flux/net radiation ratio from spectral data”, *Agricultural and Forest Meteorology*, 49 (3), pp. 205-223, 1990.

[19] Monteith, J.L., “Principles of environmental physics”, *Edward Arnold Press*, Second edition, London, pp. 241, 1973.