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Evaluation of Reference Evapotranspiration Equations under Current Climate Conditions of Egypt

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A B S T R A C T

Precise estimation of the reference evapotranspiration is very important and vital in different fields such as agriculture, hydrology and meteorology. The aim of the current study was to evaluate the performance of different reference evapotranspiration methods compared to Class-A pan or E-pan over different agro-climatic regions in Egypt. In this study, Egypt has divided into several agro-climatic regions according to the average air temperature and the reference evapotranspiration from Class-A pan. These were Nile Delta in the north, middle and Upper Egypt. Four reference evapotranspiration (ET_o) methods namely; Blaney-Criddle, Hargreaves, Thornthwaite and FAO-56 Penman-Monteith (PM) have been evaluated in this study. The results revealed that, there were statistically no significance between E-Pan and PM at P-value less than 0.05, while the other equations had significant differences. The Hargreaves equation reported the highest ET_o value at all regions while Thornthwaite was the lowest one. The difference percentage ratios between FAO-56 Penman-Monteith, Blaney-Criddle, Thornthwaite and Hargreaves and E-Pan were 3.7, -13.3, -24.8 and 10.7 respectively. Hence, FAO-56 Penman-Monteith method has proved its capability in estimation of reference evapotranspiration over different agro-climatic regions in Egypt. Therefore, it could be used over any region in Egypt especially those have no reference evapotranspiration instruments.This study is a regional research, similar studies has been made for different regions by many researchers. Therefore, the determined results in this study can be used for regions with similar climatic conditions.

Introduction

Evapotranspiration consists of different interaction components and processes in the environment, so it is one of the very complex phenomenon in its nature. Therefore, the actual water use from the water bodies and surfaces covered with plants are vital and necessary in shaping different mechanisms in our environment. Evapotranspiration is a combination of two terms, evaporation from the soil surface and transpiration from plants. The amount of evapotranspiration depends mainly on the weather and climate conditions in addition to many other factors such as crop characteristics, management and environmental factors in addition to crop species and crop growth stages. This amount plays an important and major role in agriculture and hydrology, especially the hydrological cycle. Also in meteorology, this amount determines the formation of different cloud patterns hence controls the precipitation over different locations. Scientists from different disciplines such as agronomy, hydrology, and meteorology are using different methods to estimate evapotranspiration. Modi (2000) has defined evapotranspiration as the total quantity of water used by the vegetative growth of a given area through transpiration and the buildup of plant tissue, and the total quantity that evaporated from the adjacent soil in an area at any specified period. Therefore, it includes the water removed from the soil by transpiration and evaporation. According to Nour El-Din (2013), the rate of water uptake that would sustain normal plant growth at any time depends not only upon soil water status but also upon the atmospheric conditions; these conditions determine the evapotranspiration demand.

Evapotranspiration can be classified into two types according to climatic and environmental and management conditions. To differentiate between these types, Food and Agriculture Organization (FAO 56) defined two types of evapotranspiration. These are reference evapotranspiration or reference crop evapotranspiration (ET_0) and crop evapotranspiration (ET_C). ET_0 depends only on the climatic conditions and expressing the evaporation power of the atmosphere. While, ET_C depends on the environmental and management factors under the given climatic conditions. This study is going to focus only on the reference evapotranspiration, hence dealing with different methods to estimate its amount compared to measurements from Class-A pan. Therefore, the main objective of this research study is to evaluate the performance of different reference evapotranspiration equations compared to Class-A pan over different agro-climatic regions in Egypt (Nile Delta in the north, middle and Upper Egypt). Class-A pan considered as one of the most dominant methods to measure evapotranspiration through the evaporation rate from the pan multiplied by the pan coefficient. For example, Stanhill (1965) concluded that Class-A pan was one of the most promising methods for estimating an accurate amount of reference evapotranspiration. On the other hand, Doorenbos and Pruitt (1977) introduced guidelines for choosing suitable value for the pan coefficient related to different climatic and site conditions.

Many scientists had developed several methods to estimate reference evapotranspiration using climate variables such as radiation, temperature, wind speed, and vapor pressure deficit. Most of these methods are empirical in its origin as it based on real measurements. Penman (1948) developed a semi empirical formula to estimate the reference evapotranspiration through combining both energy budget and mass transfer based on the meteorological parameters. Monteith (1965) derived a new method known as Penman-Monteith equation or combination method, which based on Penman. This method is estimating the amount of water evaporation from the vegetated surfaces. Allen et al., (1998) had developed a new formula based on Penman-Monteith known as FAO Penman-Monteith or FAO-56 PM.

Hargreaves and Samani (1985) have developed an empirical approach known as Hargreaves method for computing daily reference evapotranspiration. The original Hargreaves formula estimates the reference evapotranspiration based on solar radiation and temperature, so it used over the sites that have limited weather data.

Thornthwaite (1948) and Thornthwaite and Mather (1957) had developed an expression for estimation of evapotranspiration in terms of mean air temperature and number of monthly daylight hours.

Blaney and Criddle (1952) had developed very simple formula to estimate reference evapotranspiration based on mean daily temperature over each month. Therefore, it considered the easiest calculation method in reference evapotranspiration estimation.

Calibration and validation of all these methods are very important to evaluate its performance in comparison to the measurements, especially from the Class-A Pan.

Jensen et al. (1990) found that radiation methods considerably underestimated evapotranspiration for rates greater than 4 mm/day. George et al. (2002) have developed decision support system for estimating reference evapotranspiration using temperature, radiation and combination methods (Hidalgo et al., 2005; Irmak et al., 2003). The results obtained from the use of Hargreaves model had reported to produce satisfactory results in computing weekly or monthly reference evapotranspiration (Hargreaves and Allen, 2003). While, the Blaney-Criddle method had proven accurate estimation at the monthly time-step basis (Ray and Dadhwal, 2001).

Temesgen et al. (2005) reported that Penman-Monteith method considered as standard method compared to other methods. In addition, results from Xu and Singh (2001 and 2002), showed that equation performed best using both the original and modified constants in comparison to six other temperature-based ET_o equations, for it yielded the least error when the mean differences between the equations and pan evaporation estimates were compared. Penman-Monteith, the method which served as basis for the development of the ET_o calculator software, is considered the most physical and reliable method and is often used as a standard to verify other empirical methods (Allen et al., 2005 and Dirk 2009).

Due to the higher performance of FAO-56 Penman-Monteith (FAO-56 PM) model in different parts of the world when compared with other models, it had accepted as the sole method of computing reference evapotranspiration from meteorological data (Garcial et al., 2006).

Materials and Methods

An extensive observed climate data set for the period 1971-2000 has adopted as the base period from which climate changes are calculated. It is also the most recent 30-years World Meteorological Organization normal period; a period for which extensive non-climatic baseline data are available, and a period close enough to the present to make it possible to interpret the significance of calculated changes. The mean annual temperature data for the baseline climate period 1971-2000 have downloaded and downscaled from ClimaScope website.

Meteorological parameters, viz.: Maximum and minimum temperature, maximum and minimum relative humidity, wind speed and sunshine duration were collected for the period 1998-2007 from automated meteorological stations distributed all over Egypt. In addition to the measurements of the reference evapotranspiration using Class-A pan. These stations managed and controlled by the Central Laboratory for Agriculture Climate (CLAC), the Egyptian Ministry of Agriculture. These data used to estimate the reference evapotranspiration over Egypt using different calculation methods. These are Blaney-Criddle, Thornthwaite, Hargreaves and FAO-56 Penman-Monteith (PM). The first two methods based on the air temperature, while the other ones on the solar radiation. The results from these methods are going to be compared with the measurements from E-pan.

In this study, Egypt divided into several agro-climatic regions according to the average air temperature and the reference evapotranspiration from E-pan. The most important agro-climatic regions are; the Delta region, represented in this study by Gharbiya governorate; the Middle Egypt region represented by Menya governorate and the Upper Egypt region represented by Sohag governorate. Due to the uneven corresponding borders of the studied governorates with the latitude, we could characterize approximately the location of Upper Egypt region between (24^oN – 28^oN), Middle Egypt region between (28^oN –30^oN) and Delta region between (30^oN – 31^oN).

Statistical analysis was carried out using Statistical Analysis System (SAS) software. The paired t-test was used to establish whether there exist significant differences in the ET_0 values under different equation at significant level 0.05 (SAS, 2000).

Potential evaporation

E-pan (Class-A pan): The used A pan was circular with a diameter of 1.21 m and depth of 255 mm which gives it a volume of about 0.3 m^3. The basin is put on a 150 mm high wooden frame due to air circulation around the basin. The water level is kept about 50 mm below the rim, due to allowance of percolation and the need of water. The water level is measured every day; the value of A pan was modified.

$$ET_0 = Kp.E - pan \qquad \text{(Eq1)}$$

E-pan = pan evaporation in mm/day and represents the mean daily value of the period considered

Kp = pan coefficient (0.85 under Egyptian conditions)

FAO- 56 PM Equation: The ET_0 was estimated according to Allen et al. (1998). The FAO Penman – Monteith method to estimate reference crop evapotranspiration is as follows;

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a}{\Delta + \gamma(1 + 0.34U_2} \qquad \text{(Eq2)}$$

Where:
ET_0 = reference evapotranspiration (mm day^{-1}),
Rn = net radiation at the crop surface (MJ m-2 day^{-1}),
G = soil heat flux density (MJ m-2 day^{-1}),
T = mean daily air temperature at 2 m height (°C),
U_2 = wind speed at 2 m height (m s^{-1}),
e_s = saturation vapor pressure (kPa),
e_a = actual vapor pressure (kPa),
e_s-e_a = saturation vapor pressure deficit (kPa),
Δ = slope vapor pressure curve (kPa $°C^{-1}$),
γ = psychrometric constant (kPa $°C^{-1}$).

Hargreaves method

The Hargreaves method (Hargreaves and Samani 1985) of computing daily reference evapotranspiration is another empirical approach that was used in cases where the availability of weather data is limited. The method was developed in Davis, California from a lysimeter study on Alta fescue grass. The original Hargreaves formula calculates reference evapotranspiration from solar radiation and temperature as follows;

$$ET_0 = 0.0135\frac{R_s}{\lambda}(T + 17.8) \qquad \text{(Eq3)}$$

Where:
ET_0 = Reference evapotranspiration, (mm/day),
λ = Latent heat of vapourization, (MJ/kg) (2.45 MJ/kg),
R_s = Solar radiation, (MJ/m^2 d^{-1}),
T = Mean air temperature, (^oC).

Thornthwaite

Thornthwaite (1948) and Thornthwaite and Mather (1957) developed an expression for PET in terms of mean air temperature and number of monthly daylight hours:

$$ET_0 = 16N_m\left(\frac{10\bar{T}_m}{I}\right)^a \qquad \text{(Eq4)}$$

Where:
ET_0 = reference evapotranspiration (mm day^{-1}),
N_m = the monthly adjustment factor related to hours of daylight
$\bar{T}_m$ = mean monthly temperature in ºC
I = heat index for the year, described by Eq. 5
a = location dependent coefficient described by Eq. 6

In order to determine (*a)* and monthly ET_0, a heat index ***I*** must first be computed:

$$I = \sum_{j=1}^{j=12}\left[\frac{T_j}{5}\right]^{1.514} \qquad \text{(Eq5)}$$

Where:
T_j = the mean monthly temperature during month j (ºC) for the location of interest.

Then, the coefficient **a** can be computed as follows:

$$a=6.75x10^{-7}I^3–7.71x10^{-5}I^2+1.792x10^{-2}I+0.49239 \qquad \text{(Eq6)}$$

Blaney-Criddle formula: This formula, based on another empirical model, requires only mean daily temperatures T (ºC) over each month. Then:

$$ET_0 = p.(0.46.T + 8).mmday^{-1} \qquad \text{(Eq7)}$$

Where ET_0 reference evapotranspiration (mm day^{-1}), *p* is the mean daily percentage (for the month) of total annual daytime hours.

Results and Discussion

Figure (1) shows the distribution of annual mean air temperature for the different agro-climatic zones: Delta, Middle and Upper Egypt under baseline climate conditions 1971-2000. It has noticed that, the annual mean air temperature in middle Egypt is 21.4°C while in Delta region is 19.8°C and the highest one recorded in Upper Egypt with value 23.2°C. On the other hand, Table (1) shows the average annual ET_0 under current condition had the same trend, the highest ET_0 was found in Upper Egypt (6.41 mm) followed by middle Egypt (5.17 mm); while the lowest ET_0 value was obtained at Delta (4.18 mm). Moreover, Table (1) shows the values of monthly

ET_0 measured by E-pan. It has noticed that, there were significant differences between Delta and Middle Egypt on one hand and Delta and Upper Egypt on the other hand. The highest monthly ET_0 was recorded in Upper Egypt during all months followed by Middle Egypt then Delta. Hence, there were distinguished differences between the agro-climatic regions. These results agreed with several previous studies (Abdrabbo et al., 2015; Farag et al., 2013; Irmak et al., 2003).

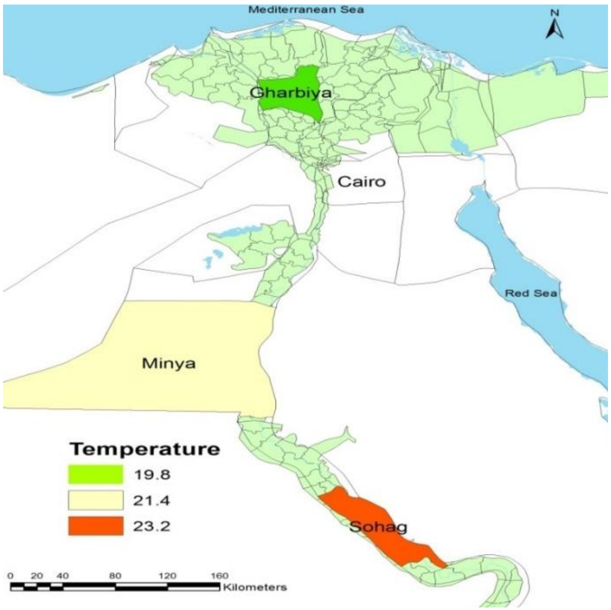

Figure 1 The distribution of annual mean air temperature for the different agro-climatic zones (Delta, Middle and Upper Egypt) according to the baseline climate 1971-2000.

Table 1 Monthly average ET_0 from E-pan for the different Agro-climatic zones (Delta, Middle and Upper Egypt) under current conditions

Month	Delta	Middle Egypt	Upper Egypt
Jan	2.24	1.94	2.64
Feb	2.72	2.57	3.36
Mar	2.72	3.68	5.20
Apr	4.36	6.30	7.82
May	5.86	8.10	9.27
Jun	6.60	8.90	10.54
Jul	6.38	8.30	10.03
Aug	5.74	7.20	9.69
Sep	4.80	6.30	7.31
Oct	3.36	3.76	4.88
Nov	3.18	2.90	3.52
Dec	2.24	2.10	2.72
Average	4.18	5.17	6.41
Annual	1527	1888	2342
P-Value		*	*

*Significant at P<0.05

Table (2) and Fig.(2) illustrate the results of monthly average calculations of ET_0 using Penman-Monteith, Blaney-Criddle, Thornthwaite and Hargreaves equations compared to E-pan for the Delta, Middle and Upper Egypt regions under current climate conditions. It is obvious from the E-pan measurements that, Upper Egypt had the highest values in both monthly and annually averages of ET_0 followed by middle Egypt, while Delta had the lowest ones. These annual values of ET_0 were; 2342 mm/year, 1888 mm/year and 1527 mm/year for Upper Egypt; middle Egypt and Delta respectively.

Regarding the estimated monthly average of ET_0 values, all equations had the same trend and behavior like E-pan at all agro-climatic regions. The highest values of measured and estimated ET_0 for all regions were recorded during June and July months, while the lowest ones were recorded in January and February. In addition, it is noticed that ET_0 values were gradually increased from January till July as the temperature increases then decreasing trend from June to December as the temperature decreases. Statistically, there were no significant differences between E-pan and PM at different climatic regions on one hand, while it were significant with the other tested equations on the other hand. Hence, PM is considered as the best equation in ET_0 estimation compared to the other equations at different climatic regions in Egypt. In addition, the highest estimated annual values of ET_0 were given using Hargreaves equation, while the lowest ones were given by Thornthwaite equation at all agro-climatic regions.

The percentage of differences of different tested ET_0 equations compared to E-pan (Table 3 and Fig. 3) show that, PM and Hargreaves gave higher values than E-pan by 3.7% and 10.7% respectively, while Blaney and Criddle, Thornthwaite gave lower values than E-pan by -13.3% and -24.8% respectively. Moreover, the differences percentage of different tested equations increased in Upper Egypt compared to Middle Egypt and Delta. PM considered the best equation especially in Delta because it has the lowest differences from E-pan about 1.8% compared to E Pan. Hence, the results revealed that, estimated ET_0 values by Pemann-Monteith method are very close to the observed one compared to the other methods in all regions. However, Hargreaves method gave higher estimated values than E-pan (Fig 3). On the other hand, the lowest values had been estimated using Thornthwaite method for all agro-climatic regions. Therefore, Penman-Monteith equation shows high performance and Thornthwaite equation has low performance in all regions. Therefore, one may conclude that PM could be used in estimation of the reference evapotranspiration over different agro-climatic regions in Egypt with high performance comparable to other methods.

These results agreed with Ayub and Miah (2011); Gad and El-Gayar, (2010); Nour El-Din (2013); and Temesgen et al. (2005).

Table 2 Comparison between estimated monthly average of ET_0 using Penman-Monteith, Blaney-Criddle, Thornthwaite, Hargreaves methods and E-pan for different agro-climate regions.

Month	E-Pan	Penman-Monteith	Blaney-Criddle	Thornthwaite	Hargreaves
Delta					
Jan	2.24	1.95	2.79	2.25	2.60
Feb	2.72	2.32	2.82	2.28	2.80
Mar	2.72	2.63	3.51	2.28	3.30
Apr	4.36	4.46	3.63	3.09	4.90
May	5.86	5.78	4.31	3.93	5.88
Jun	6.60	6.43	5.66	5.45	6.12
Jul	6.38	6.25	5.66	5.88	6.23
Aug	5.74	5.85	5.50	4.99	5.60
Sep	4.80	5.18	4.97	4.78	5.72
Oct	3.36	4.42	4.35	4.11	4.24
Nov	3.18	3.34	3.48	3.08	3.67
Dec	2.24	2.50	2.98	2.43	3.28
Average	4.18	4.26	4.14	3.71	4.53
Annual	1527	1555	1510	1355	1653
P-Value		N.S.	*	*	*
Middle					
Jan	1.94	2.17	3.28	2.05	2.91
Feb	2.57	2.98	3.31	2.08	3.56
Mar	3.68	3.37	3.57	2.20	4.32
Apr	6.30	6.40	4.19	3.15	6.78
May	8.10	7.47	5.04	4.20	6.51
Jun	8.90	8.30	6.21	5.80	8.32
Jul	8.30	7.98	6.14	6.09	8.21
Aug	7.20	7.61	5.95	5.18	8.19
Sep	6.30	7.43	5.37	4.88	7.27
Oct	3.76	5.11	4.67	4.16	5.78
Nov	2.90	3.64	3.84	2.95	4.61
Dec	2.10	2.52	3.26	2.25	3.14
Average	5.17	5.41	4.57	3.75	5.80
Annual	1888	1976	1667	1368	2117
P-Value		N. S.	*	*	*
Upper					
Jan	2.64	2.58	3.27	2.16	3.16
Feb	3.36	3.42	3.30	2.19	3.79
Mar	5.20	4.27	3.61	2.36	5.02
Apr	7.82	7.85	4.35	3.57	8.72
May	9.27	9.59	5.29	4.81	10.50
Jun	10.54	10.27	6.49	6.56	10.88
Jul	10.03	10.31	6.34	6.84	10.89
Aug	9.69	10.43	6.13	5.72	10.43
Sep	7.31	8.58	5.52	5.42	9.28
Oct	4.88	5.74	4.77	4.52	5.47
Nov	3.52	4.45	3.87	3.16	4.56
Dec	2.72	3.02	3.25	2.35	3.25
average	6.41	6.71	4.68	4.14	6.85
annual	2342	2449	1709	1511	2614
P-Value		N. S.	*	*	*

*Significant at $P<0.05$

Table 3 Average annual estimated ET_0 under different agro-meteorological regions using Penman-Monteith, Blaney-Criddle,Thornthwaite and Hargreaves equations and Differences Percentage from E pan .

Region	E-pan	Penman-Monteith	Blaney - Criddle	Thornthwaite	Hargreaves	average
Nile Delta	1527	1555	1510	1355	1653	1518
Middle Egypt	1888	1976	1667	1368	2117	1782
Upper Egypt	2342	2449	1709	1511	2614	2071
	1919	1994	1629	1412	2128	
Differences Percentage from E pan						
Nile Delta	0.0%	1.8%	-1.1%	-11.3%	8.2%	-0.6%
Middle Egypt	0.0%	4.7%	-11.7%	-27.5%	12.2%	-5.6%
Upper Egypt	0.0%	4.6%	-27.0%	-35.5%	11.6%	-11.6%
	0.0%	3.7%	-13.3%	-24.8%	10.7%	

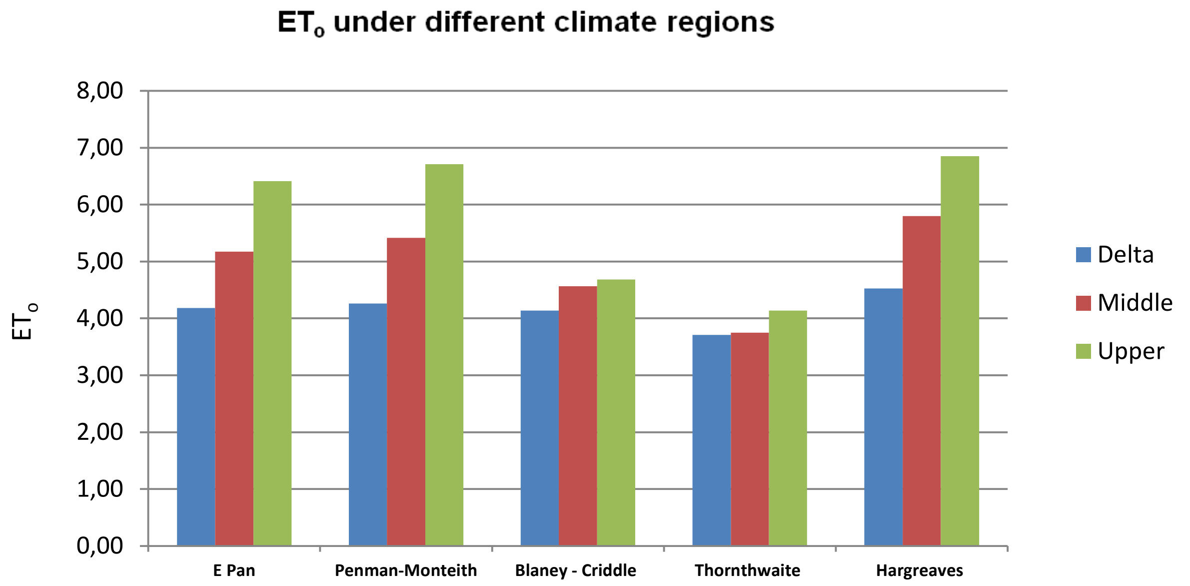

Figure 2 Average ETo calculated by different mathematical equations under different climatic regions.

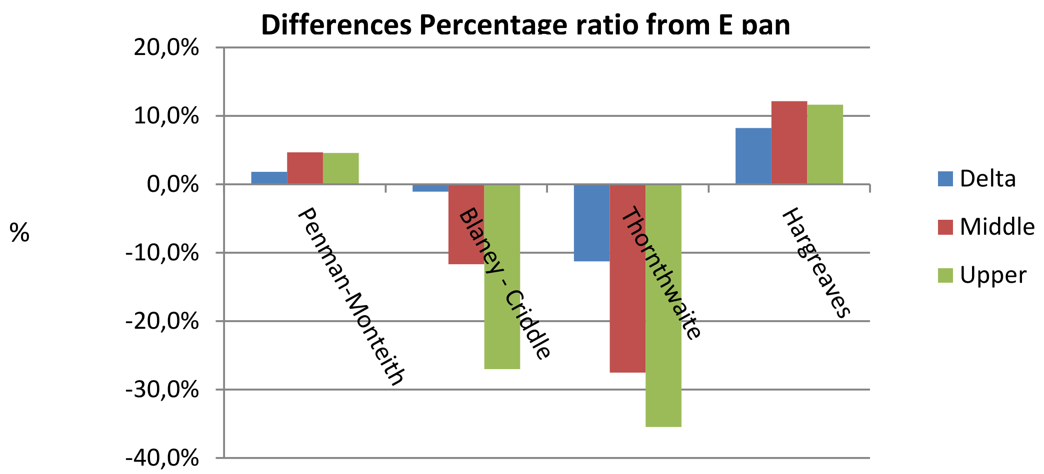

Figure 3 Differences percentage ratio of ETo calculated by different mathematical equations under different climatic regions compared to E-pan.

Summary and Conclusion

In this study, the evaluation of different reference evapotranspiration methods against the Class-A pan measurements over Egypt was investigated. These are Blaney-Criddle, Thornthwaite, Hargreaves and FAO-56 Penman-Monteith (PM). The first two methods based on the air temperature, while the other ones based on the solar radiation. Egypt had divided into three agro-climatic regions (Nile Delta in the north, middle and Upper Egypt) according to the mean annual temperature (1971-2000) and the reference evapotranspiration measurements (1998-2007). The mean annual temperature records has been downloaded from the ClimaScope website http://climascope.tyndall.ac.uk/, using downscaling technique. While, the meteorological parameters had collected from the automated meteorological stations distributed over Egypt. In addition to the measurements of the reference evapotranspiration using Class-A pan or E-pan.

The results revealed that, FAO-56 PM have proved high performance reference evapotranspiration estimation all over the three distinct agro-climatic zones over Egypt compared to the other methods. Therefore, one might conclude that PM-56 could use in estimation of the reference evapotranspiration over different agro-climatic regions in Egypt with high performance comparable to other methods.

This study is a regional research, similar studies has been made for different regions by many researchers. Therefore, the determined results in this study can be used for regions with similar climatic conditions.

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