Chapter 1
Evapotranspiration Under Changing Climate

Samiha Ouda, Tahany Noreldin and Mohamed Hosney

Abstract This chapter described methodology to calculate evapotranspiration (ET) values similar to the values calculated with Penman–Monteith equation (P–M), using ET values calculated by Hargreaves–Samani equation (H–S) under current and climate change. The BISm model was used to calculate monthly values of ET using P–M and H–S equations using weather data averaged over 10 years, from 2004 to 2013 for each of the 17 studied governorates and the values were compared. The comparison showed that there were deviations between monthly ET values calculated for each equation in each governorate. Thus, a linear regression equation was established with ET values resulted from P–M plotted as the dependent variable and ET values from H–S equation plotted as the independent variable. The quality of the fit between the two methodologies was presented in terms of the coefficient of determination (R^2) and root mean square error per observation (RMSE/obs). ECHAM5 climate change model was used to develop A1B climate change scenario for each governorate for the years 2020, 2030 and 2040, where ET values were calculated. The results indicated that R^2 was between close to one and RMSE/obs values were close to zero. The results also indicated that the calibration coefficients were capable to account for the effect of relative humidity, wind speed and potential sunshine hours, which were not included in the H–S equation. Furthermore, under A1B climate change scenario, the values of ET were increased. The above methodology could solve a large problem that faces researchers and extension workers in irrigation scheduling in Egypt and in other developing countries under current climate and in calculation of water requirements under climate change.

Keywords Penman–Monteith and Hargreaves–Samani equations · BISm model · ECHAM5 model · A1B climate change scenario

Climate plays an important role in crop production. Crops growth periods, crops water requirements, and scheduling irrigation for crops are dependent on weather conditions. The calculation of the evapotranspiration (ET) includes all the weather

S. Ouda (✉) · T. Noreldin · M. Hosney
Water Requirements and Field Irrigation Research Department, Agricultural Research Center, Soils, Water and Environment Research Institute, El Giza, Egypt

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parameters prevailed in a specific area. ET is a combination of two processes: water evaporation from soil surface and transpiration from the growing plants (Gardner et al. 1985). Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide energy for evaporation, whereas solar radiation, air temperature, air humidity, and wind speed should be considered when assessing transpiration (Allen et al. 1998). ET is a key component in hydrological studies. It is used for agricultural and urban planning, irrigation scheduling, regional water balance studies, and agro-climatic zoning (Khalil et al. 2011).

Various equations are available for estimating ET. These equations range from the most complex energy balance equations requiring detailed climatological data (Penman–Monteith; Allen et al. 1989) to simpler equations requiring limited data (Blaney–Criddle 1950; Hargreaves–Samani 1982, 1985). The Penman–Monteith equation (P–M) is widely recommended because of its detailed theoretical base and its accommodation of small time periods. The method requires maximum and minimum temperature, relative humidity, wind speed, and potential sunshine hours, whereas Hargreaves–Samani equation (H–S) requires three weather parameters only: maximum and minimum temperatures and solar radiation.

This chapter described methodology to calculate ET values similar to the values calculated with P–M equation, using ET values calculated by H–S equation.

BISm Model Description

The Basic Irrigation Scheduling model (BISm) was written using MS Excel to help people plan irrigation management of crops. The BISm model calculates ET using the Penman–Monteith (P–M) equation (Monteith 1965) as presented in the United Nations FAO Irrigation and Drainage Paper (FAO, 56) by Allen et al. (1998). If only temperature and solar radiation data are input, Hargreaves–Samani equation is used (Snyder et al. 2004). The weather station latitude and elevation must also be input. After calculating daily means by month, a cubic spline curve fitting subroutine is used to estimate daily ET rates for the entire year.

The BISm model was used to calculate monthly ET values as an average over 10 years, from 2004 to 2013 for each of the 17 studied governorates using P–M equation. Furthermore, ET values using H–S equation for these governorates were calculated and then compared to ET values of P–M equation.

Comparison Between ET(P–M) and ET(H–S) Values

The calculated values of ET(P–M) and ET(H–S) in each governorate were graphed to ease comparison. The results for Alexandria (Fig. 1.1), Demiatte (Fig. 1.2), Kafr El-Sheik (Fig. 1.3), and El-Dakahlia (Fig. 1.4) showed that during summer months, the H–S equation underestimated ET values.

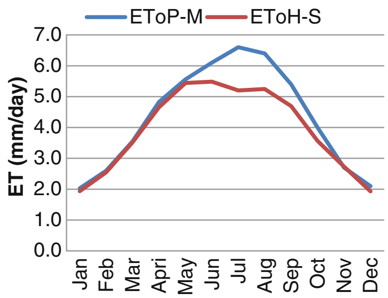


Fig. 1.1 Comparison between ET(P–M) and ET(H–S) in Alexandria governorate

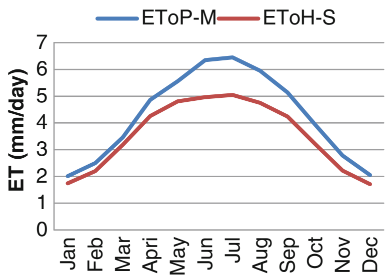


Fig. 1.2 Comparison between ET(P–M) and ET(H–S) in Demiatte governorate

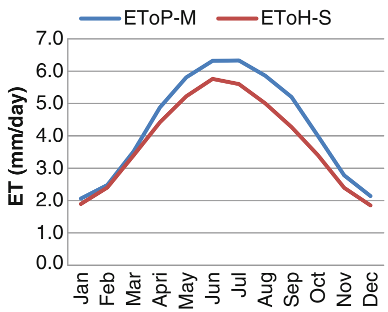


Fig. 1.3 Comparison between ET(P–M) and ET(H–S) in Kafr El-Sheik governorate

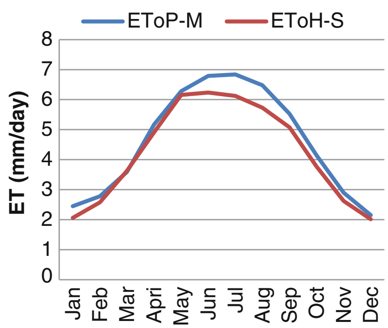


Fig. 1.4 Comparison between ET(P–M) and ET(H–S) in El-Dakahlia governorate

Regarding to El-Behira and El-Gharbia, the deviation of ET(H–S) from ET(P–M) was high during all the year, especially in the summer months (Figs. 1.5 and 1.6). Similarly, Figs. (1.7 and 1.8) show the same trend in Assuit and Aswan governorates. However, the deviation in the winter months became higher.

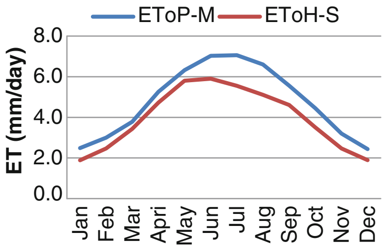


Fig. 1.5 Comparison between ET(P–M) and ET(H–S) in El-Behira governorate

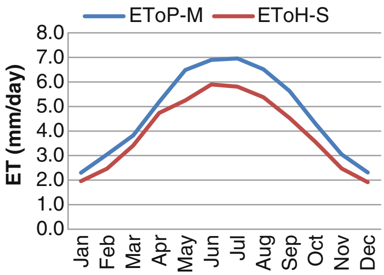


Fig. 1.6 Comparison between ET(P–M) and ET(H–S) in El-Gharbia governorate

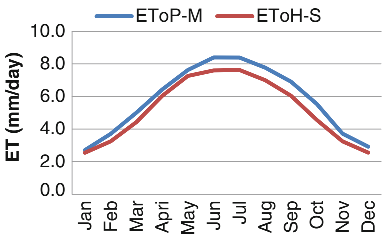


Fig. 1.7 Comparison between ET(P–M) and ET(H–S) in Assuit governorate

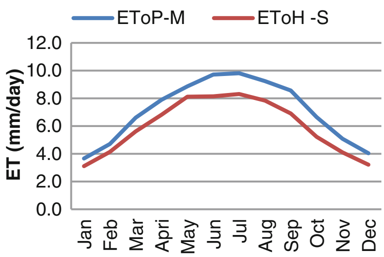


Fig. 1.8 Comparison between ET(P–M) and ET(H–S) in Aswan governorate

With respect to El-Monofia, Fig. (1.9), and El-Sharkia (Fig. 1.10), the values ET (P–M) and ET(H–S) were close to each other from January to May, and then the deviations were higher in the months after.

In El-Kalubia governorate (Fig. 1.11), the situation was different, where low deviation was observed only in the summer months, whereas there was no deviation between the values of ET(P–M) and ET(H–S) for the rest of the months. Similar trend was observed in Beni Swief governorate with higher deviation from May to August (Fig. 1.12). In El-Minia governorate, the deviation was very low (Fig. 1.13), and in Suhag governorate (Fig. 1.14), the deviation was higher from May to July.

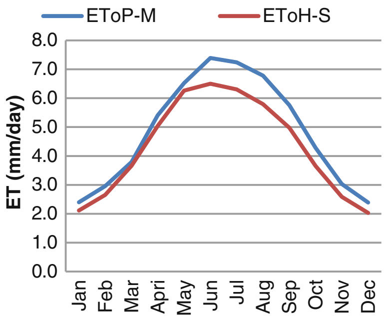


Fig. 1.9 Comparison between ET(P–M) and ET(H–S) in El-Monofia governorate

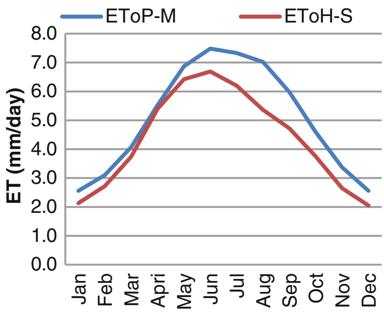


Fig. 1.10 Comparison between ET(P–M) and ET(H–S) in El-Sharkia governorate

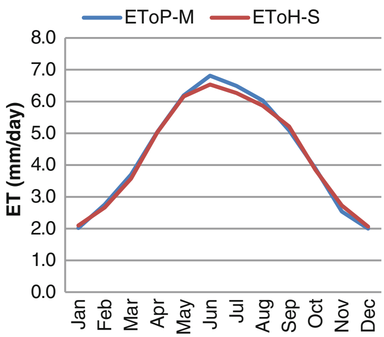


Fig. 1.11 Comparison between ET(P–M) and ET(H–S) in El-Kalubia governorate

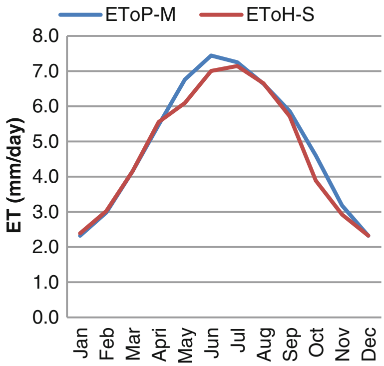


Fig. 1.12 Comparison between ET(P–M) and ET(H–S) in Beni Swief governorate

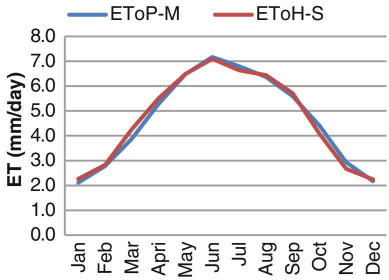


Fig. 1.13 Comparison between ET(P–M) and ET(H–S) in El-Minia governorate

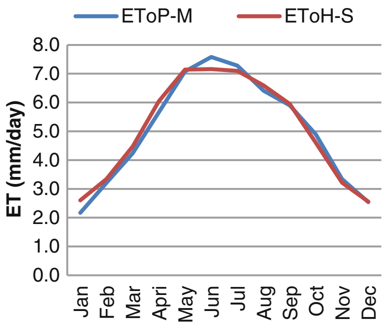


Fig. 1.14 Comparison between ET(P–M) and ET(H–S) in Suhag governorate

The difference between ET(P–M) and ET(H–S) for El-Giza (Fig. 1.15) and El-Fayoum (Fig. 1.16) was low for most of the months.

Regarding to Qena governorate, there was no difference between values of ET (P–M) and ET(H–S) in June and July. However, for the rest of the months, there were no differences (Fig. 1.17).

The above comparison showed that there were deviations between monthly ET values calculated for each equation in each governorate. Therefore, to increase the accuracy of the estimation, a linear regression equation was established with ET values resulted from P–M plotted as the dependent variable and ET values from H–S

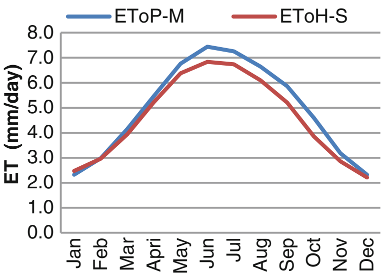


Fig. 1.15 Comparison between ET(P–M) and ET(H–S) in Giza governorate

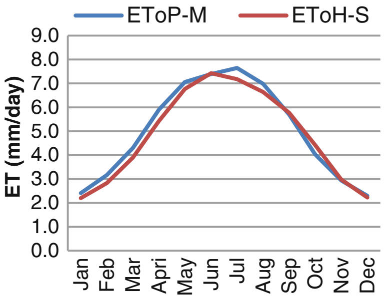


Fig. 1.16 Comparison between ET(P–M) and ET(H–S) in El-Fayoum governorate

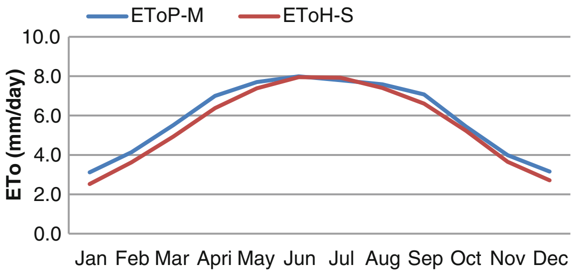


Fig. 1.17 Comparison between ET(P–M) and ET(H–S) in Qena governorate

equation plotted as the independent variable. The intercept (a) and calibration slope (b) of the best fit regression line were used as regional calibration coefficients for each governorate. This methodology was developed by Shahidian et al. (2012) as follows:

$$\mathrm{ET(P-M) = a + b * ET(H{-}S)}. \tag{1.1}$$

An equation for each governorate was developed, where different (*a*) and (*b*) values were estimated. The quality of the fit between the two methodologies was presented in terms of the coefficient of determination (R^2), which is the ratio of the explained variance to the total variance and through calculation of root-mean-square error per observation (RMSE/obs), which gives the standard deviation of the model prediction error per observation (Jamieson et al. 1998). Regression equations,

Table 1.1 Prediction equations, coefficient of determination (R^2), and root-mean-square error per observation (RMSE/obs) for ET values in the studied governorates

Governorate	Prediction equation	R^2	RMSE/obs
Nile Delta			
Alexandria	ET(P–M) = −0.4252 + 1.2134*ET(H–S)	0.95	0.06
Demiatte	ET(P–M) = −0.2297 + 1.2714*ET(H–S)	0.98	0.05
Kafr El-Sheik	ET(P–M) = −0.1280 + 1.1690*ET(H–S)	0.98	0.05
El-Dakahlia	ET(P–M) = 0.0338 + 1.0745*ET(H–S)	0.98	0.04
El-Behira	ET(P–M) = 0.3432 + 1.1157*ET(H–S)	0.96	0.04
El-Gharbia	ET(P–M) = 0.2673 + 1.1019*ET(H–S)	0.97	0.04
El-Monofia	ET(P–M) = 0.0737 + 1.1640*ET(H–S)	0.98	0.05
El-Sharkia	ET(P–M) = 0.3484 + 1.0857*ET(H–S)	0.95	0.06
El-Kalubia	ET(P–M) = −0.1739 + 1.0498*ET(H–S)	0.99	0.03
Middle Egypt			
Giza	ET(P–M) = −0.1292 + 1.1050* ET(H–S)	0.99	0.04
Fayoum	ET(P–M) = 0.0702 + 1.0209* ET(H–S)	0.98	0.05
Beni Swief	ET(P–M) = 0.0015 + 1.0370* ET(H–S)	0.98	0.05
El-Minia	ET(P–M) = −0.0378 + 1.0033* ET(H–S)	0.98	0.04
Upper Egypt			
Assuit	ET(P–M) = 0.1352 + 1.1042* ET(H–S)	0.97	0.04
Suhag	ET(P–M) = −0.2569 + 1.0428* ET(H–S)	0.98	0.04
Qena	ET(P–M) = 0.7528 + 0.9270* ET(H–S)	0.99	0.03
Aswan	ET(P–M) = 0.2727 + 1.1500* ET(H–S)	0.97	0.03

coefficient of determination (R^2), and root-mean-square error per observation (RMSE/obs) are presented in Table (1.1).

The results from Table (1.1) showed that R^2 was between 0.95 and 0.99 in the Nile Delta. The variation in R^2 in Middle Egypt was between 0.98 and 0.99, whereas in Upper Egypt, the values of R^2 were between 0.97 and 0.99. Furthermore, RMSE/obs values were between 0.03 and 0.06 mm/day in Nile Delta. It was between 0.04 and 0.05 mm/day in Middle Egypt and between 0.03 and 0.04 mm/day in Upper Egypt. The presented equation for each governorate was used to predict monthly values of ET(P–M).

The calibration coefficients (*a* and *b*) with ET values calculated from Hargreaves–Samani equation could be used by other researchers to predict ET values similar to the one calculated by Penman–Monteith equation for each governorate in Egypt with high degree of accuracy because R^2 for each equation was close to 1 and RMSE/obs was close to zero (Table 1.1). The calibration coefficients (*a* and *b*) should be developed for each site to increase the accuracy of prediction of ET(P–M) values.

The predicted values of ET were compared with the estimated values of ET(P–M) and graphed together to ease comparison. Regarding to Alexandria and Demiatte governorates, the predicted values were close to calculated values in most of the months (Figs. 1.18 and 1.19).

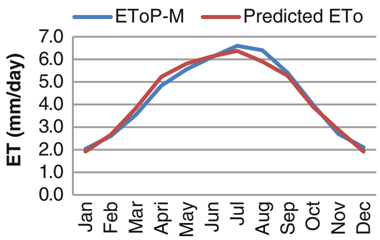


Fig. 1.18 Comparison between ET(P–M) and predicted values of ET in Alexandria governorate

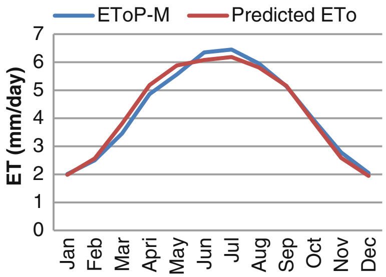


Fig. 1.19 Comparison between ET(P–M) and predicted values of ET in Demiatte governorate

Figures (1.20, 1.21, 1.22, 1.23, 1.24, 1.25, 1.26, 1.27, 1.28, 1.29, 1.30, 1.31, 1.32, 1.33, and 1.34) show that the deviation between calculated and predicted ET values was either low or not exist in the rest of governorates.

The results in the above graphs proved that the calibration coefficients were capable to account for the effect of relative humidity, wind speed, and potential sunshine hours, which not included in the H–S equation. ET values in the studied areas are presented in Table 1.2.

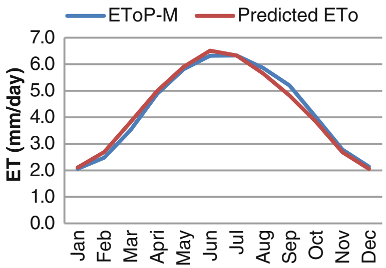


Fig. 1.20 Comparison between ET(P–M) and predicted values of ET in Kafr El-Sheik governorate

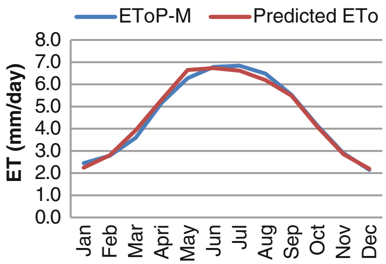


Fig. 1.21 Comparison between ET(P–M) and predicted values of ET in El-Dakahlia governorate

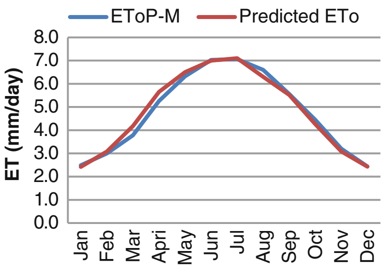


Fig. 1.22 Comparison between ET(P–M) and predicted values of ET in El-Behira governorate

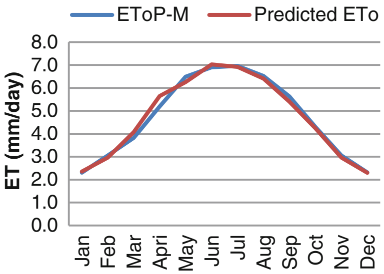


Fig. 1.23 Comparison between ET(P–M) and predicted values of ET in El-Gharbia governorate

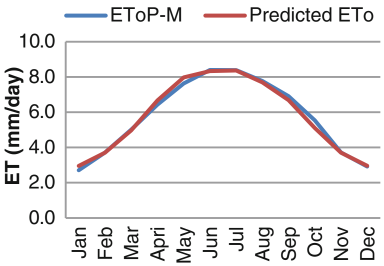


Fig. 1.24 Comparison between ET(P–M) and predicted values of ET in Assuit governorate

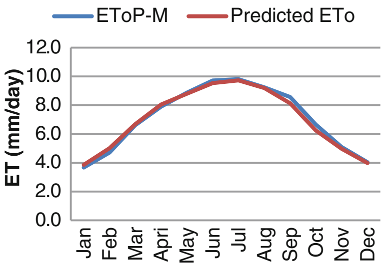


Fig. 1.25 Comparison between ET(P–M) and predicted values of ET in Aswan governorate

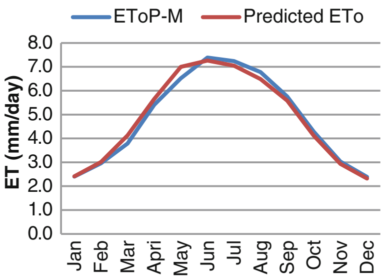


Fig. 1.26 Comparison between ET(P–M) and predicted values of ET in El-Monofia governorate

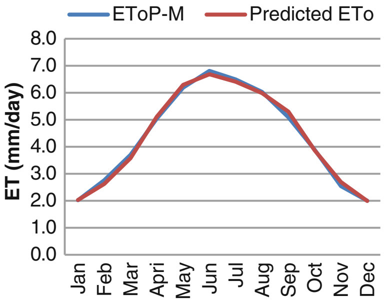


Fig. 1.27 Comparison between ET(P–M) and predicted values of ET in El-Sharkia governorate

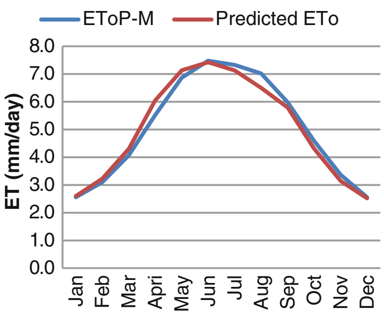


Fig. 1.28 Comparison between ET(P–M) and predicted values of ET in El-Kalubia governorate

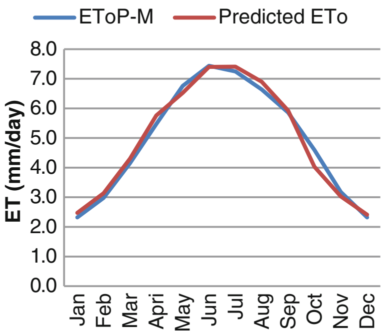


Fig. 1.29 Comparison between ET(P–M) and predicted values of ET in Beni Swief governorate

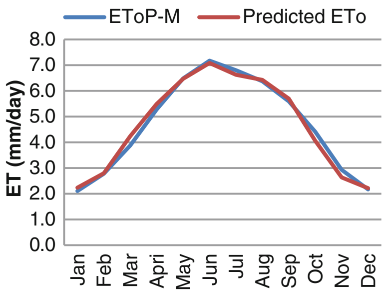


Fig. 1.30 Comparison between ET(P–M) and predicted values of ET in El-Minia governorate

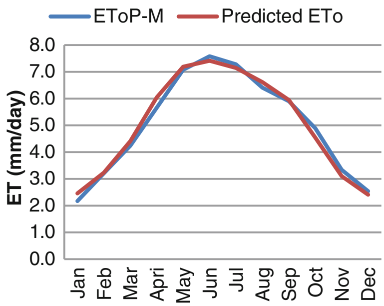


Fig. 1.31 Comparison between ET(P–M) and predicted values of ET in Suhag governorate

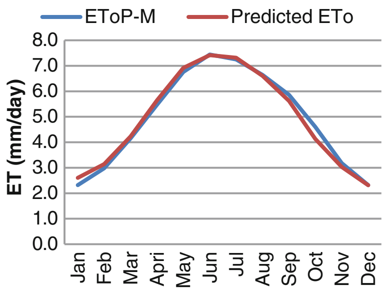


Fig. 1.32 Comparison between ET(P–M) and predicted values of ET in Giza governorate

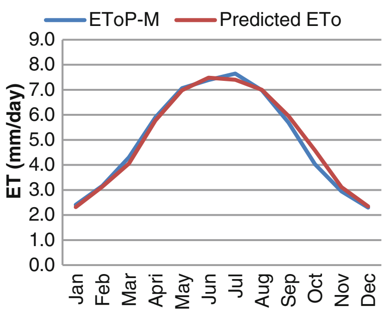


Fig. 1.33 Comparison between ET(P–M) and predicted values of ET in El-Fayoum governorate

Fig. 1.34 Comparison between ET(P–M) and predicted values of ET in Qena governorate

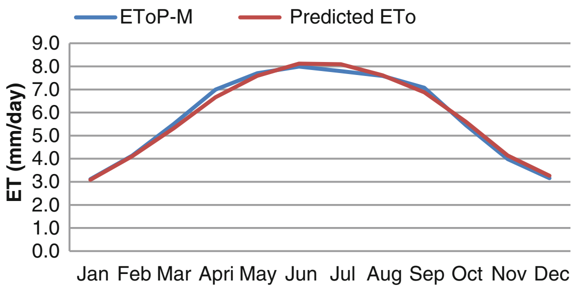


Table 1.2 Yearly average value of ET (mm/day) under current climate

Governorate	ET under current climate
Nile Delta	
Alexandria	4.32
Demiatte	4.25
Kafr El-Sheik	4.28
El-Dakahlia	4.59
El-Behira	4.79
El-Gharbia	4.71
El-Monofia	4.83
El-Sharkia	4.38
El-Kalubia	5.01
Middle Egypt	
Giza	4.91
Fayoum	5.01
Beni Swief	4.94
El-Minia	4.66
Upper Egypt	
Assuit	5.76
Suhag	5.04
Qena	5.87
Aswan	7.01

Khalil (2013) indicated that under current climate, Aswan governorate has the highest value of ET, in comparison with all other governorates, and Demiatte has the lowest value of ET, which is similar to what is presented in Table (1.2).

Similar procedure could be done using ET(P–M) values obtained from FAO AQUASTAT website: http://www.fao.org/nr/water/aquastat/gis/index3.stm. These values can be obtained for any location on Earth. The obtained values are normal weather parameters (average of 30 years from 1961 to 1990), in addition to ET values calculated using P–M equation.

Furthermore, the above methodology could solve a large problem that faces researchers and extension workers in irrigation scheduling in Egypt and in other developing countries. The availability of a number of meteorological stations, to measure weather parameters, is limited, and reliability of the measured data could be an obstacle. There are also concerns about the accuracy of the observed meteorological parameters (Droogers and Allen 2002), since the actual instruments, specifically pyranometers (solar radiation) and hygrometers (relative humidity), are often subject to stability errors, where it is common to see a drift as high as 10 % in pyranometers (Samani 2000). Sepaskhah and Razzaghi (2009) have observed that hygrometers lose about 1 % in accuracy per installed month. Thus, they recommend the use of ET equations that require fewer variables. Hargreaves and Allen (2003) concluded that the differences in ET values, calculated by the different methods, are minor when compared with the uncertainties in estimating actual crop evapotranspiration from measured weather data. Additionally, these equations can be more easily used in adaptive or smart irrigation controllers that adjust the application depth according to the daily ET demand (Shahidian et al. 2009).

Evapotranspiration Under Climate Change

The agricultural system in Egypt is vulnerable to climate change due to its limited water resources and strong dependence on irrigation for crop production. Exploring the impacts of climate change on crop evapotranspiration is important for water management and agricultural sustainability. Climate change and its syndrome, i.e., higher temperature, will increase ET and that will affect the hydrological system and water resources (Shahid 2011). In Egypt, temperature rise by 1 °C may increase ET rate by about 4–5 % (Eid 2001). Furthermore, Khalil (2013) indicated that ET values will increase under climate change compared to current climate. Thus, quantifying the changes in ET due to climate change is very important for management of water resources.

Climate Change Model

Research program on Climate Change Agriculture and Food Security (CCAFS) is one of CIGAR programs that implement a uniquely innovative and transformative research program that addresses agriculture in the context of climate variability, climate change, and uncertainty about future climate conditions. The details of the methodology are presented in Jones et al. (2009). The link to this web site is the following: http://www.ccafs.cgiar.org/marksimgcm#.Ujh1gj-GfMY. The web site is composed of seven global climate change models. For each model, three climate change scenarios (A1B, A2, and B1) can be downloaded.

The climate model ECHAM5 (Roeckner et al. 2003) is one of them and was used in this analysis. The model is Atmospheric Oceanic General Circulation model. It has been developed from the ECMWF operational forecast model cycle

36 (1989) (therefore, the first part of its name: EC) and a comprehensive parameterization package developed at Hamburg (therefore, the abbreviation HAM). The part describing the dynamics of ECHAM is based on the ECMWF documentation, which has been modified to describe the newly implemented features and the changes necessary for climate experiments. Since the release of the previous version, ECHAM4, the whole source code, has been extensively redesigned in the major infrastructure and transferred to FORTRAN 95, ECHAM is now fully portable and runs on all major high-performance platforms. The restart mechanism is implemented on top of net CDF and because of that it absolutely independent on the underlying architecture. The resolution of the model is 1.9 × 1.9°.

Climate Change Scenario

ECHAM5 model was used to develop A1B climate change scenario for each weather station in each governorate. IPCC (2007) describes the A1 storyline and scenario family as a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. One of its family is A1B, where its technological balance is across all sources (balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

The downloaded scenario was for the years 2020, 2030, and 2040 and composed of maximum and minimum temperature, rain, and solar radiation. These weather parameters were not enough to calculate ET with P–M equation. However, they are enough to calculate ET using H–S equation. The developed equations were used to calculate ET values under A1B climate change scenario in 2020, 2030, and 2040.

Calculation of ET Under A1B Climate Change Scenario

ET values under A1B climate change scenario in 2020, 2030, and 2040 were calculated for each governorate, and yearly average value was calculated. Figures (1.35, 1.36, 1.37, 1.38, 1.39,1.40, 1.41, 1.42, 1.43, 1.44, 1.45, 1.46, 1.47, 1.48, 1.49, 1.50 and 1.51) presented comparison between ET values under current climate and under A1B climate change scenario 2020, 2030, and 2040 in each governorate.

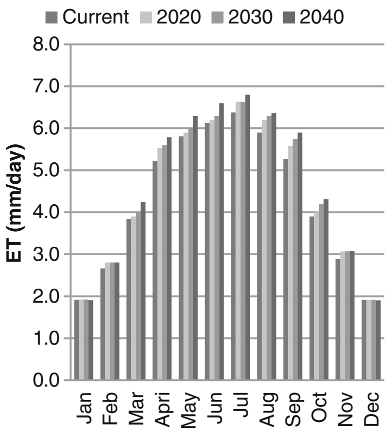


Fig. 1.35 ET values under current climate and A1B climate change scenario in Alexandria governorate

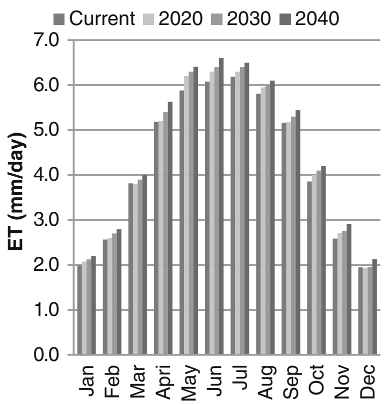


Fig. 1.36 ET values under current climate and A1B climate change scenario in Demiatte governorate

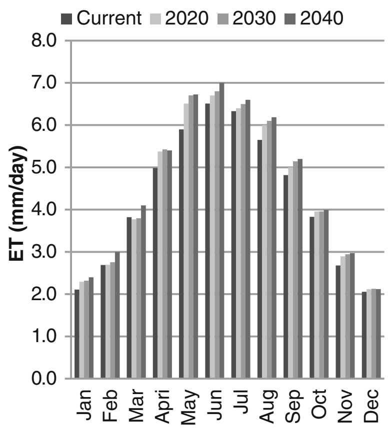


Fig. 1.37 ET values under current climate and A1B climate change scenario in Kafr El-Sheik governorate

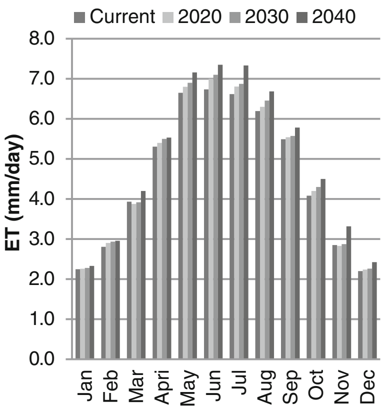


Fig. 1.38 ET values under current climate and A1B climate change scenario in El-Dakahlia governorate

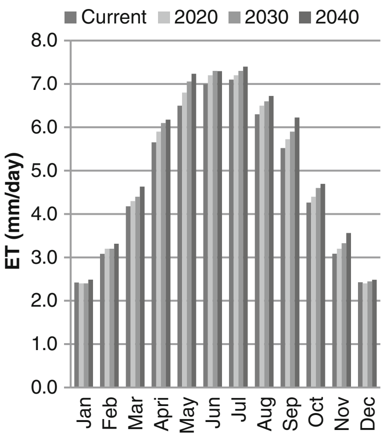


Fig. 1.39 ET values under current climate and A1B climate change scenario in El-Behira governorate

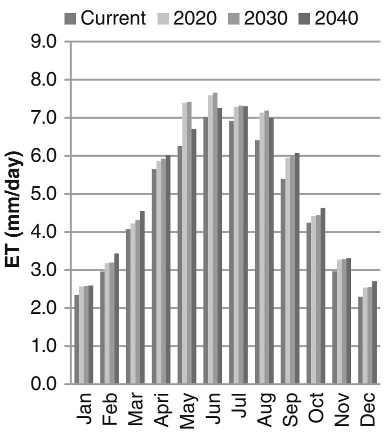


Fig. 1.40 ET values under current climate and A1B climate change scenario in El-Gharbia governorate

Fig. 1.41 ET values under current climate and A1B climate change scenario in Assuit governorate

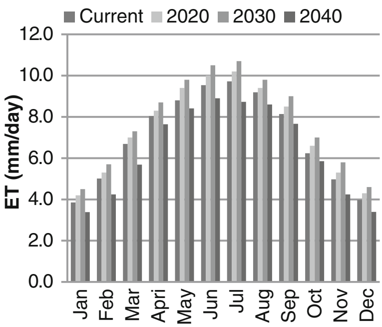


Fig. 1.42 ET values under current climate and A1B climate change scenario in Aswan governorate

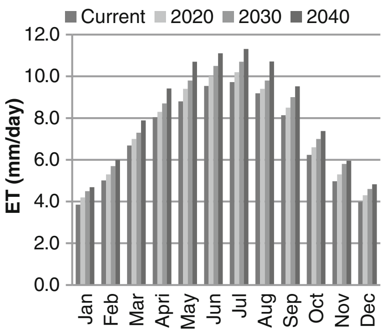
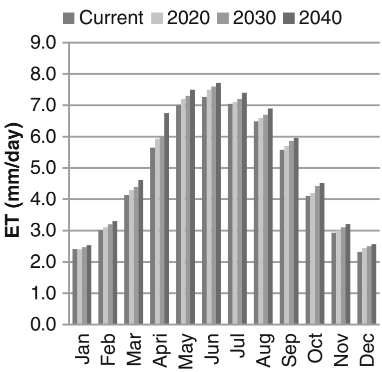


Fig. 1.43 ET values under current climate and A1B climate change scenario in El-Monofia governorate



These graphs showed that the value of monthly ET under climate change increases gradually starting from January until April and then the increase become higher during the summer months. In the fall months until December, the decrease became lower. This trend was found in all studied governorates.

The above graphs implied that under A1B climate change scenario, the value of ET will increase, and consequently water requirements for crops are expected to

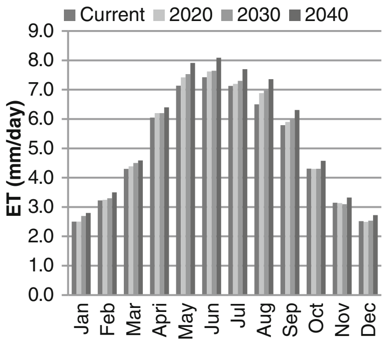


Fig. 1.44 ET values under current climate and A1B climate change scenario in El-Sharkia governorate

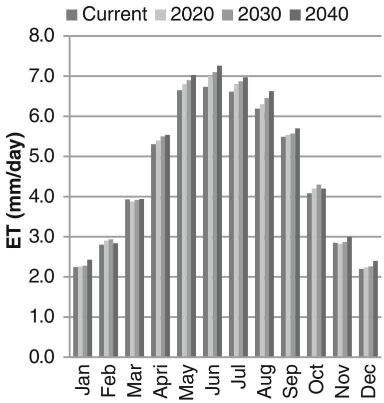


Fig. 1.45 ET values under current climate and A1B climate change scenario in El-Kalubia governorate

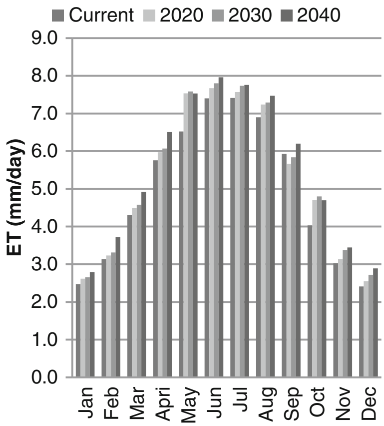


Fig. 1.46 ET values under current climate and A1B climate change scenario in Beni Swief governorate

Fig. 1.47 ET values under current climate and A1B climate change scenario in El-Minia governorate

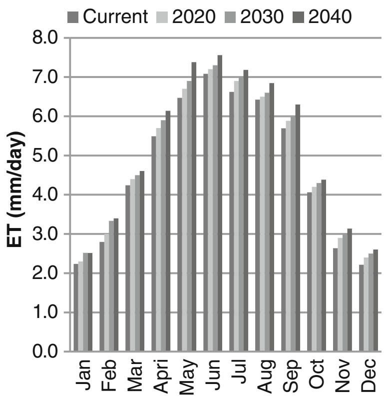


Fig. 1.48 ET values under current climate and A1B climate change scenario in Suhag governorate

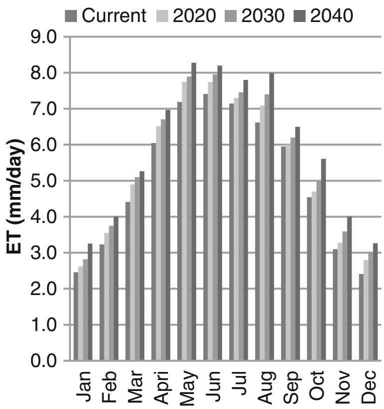
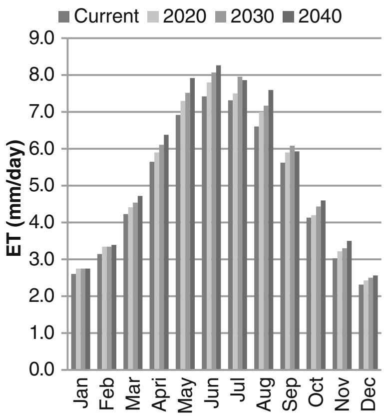


Fig. 1.49 ET values under current climate and A1B climate change scenario in El-Giza governorate



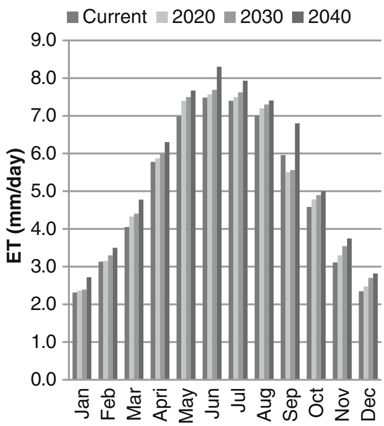


Fig. 1.50 ET values under current climate and A1B climate change scenario in El-Fayoum governorate

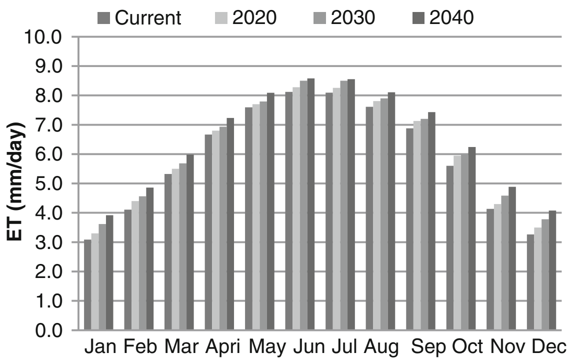


Fig. 1.51 ET values under current climate and A1B climate change scenario in Qena governorate

increase in all governorates with different values. Table (1.3) presents the percentage of increase in ET annual values in all governorates. The average ET values were 7, 9, and 13 % in 2020, 2030, and 2040, respectively. Snyder et al. (2011) concluded that the impact of global warming on ET will likely be less in locations with higher wind speeds. The northern five governorates in the Nile Delta are located on the Mediterranean Sea and characterized by high wind speeds between 4.3 and 4.9 m s^{-1}. Furthermore, the percentage of increase in ET under A1B climate change scenario was the lowest in the three tested future years in these five governorates.

Table 1.3 Percentage of increase in ET (mm/day) under A1B climate change scenario in 2020, 2030, and 2040

Governorate	ET in 2020	ET in 2030	ET in 2040
Nile Delta			
Alexandria	1	3	4
Demiatte	1	2	2
Kafr El-Sheik	2	2	2
El-Dakahlia	1	1	2
El-Behira	1	2	2
El-Gharbia	7	10	19
El-Monofia	5	10	19
El-Sharkia	7	14	17
El-Kalubia	7	11	19
Middle Egypt			
Giza	8	15	16
Fayoum	8	12	16
Beni Swief	10	13	18
El-Minia	10	15	19
Upper Egypt			
Assuit	11	12	17
Suhag	12	10	18
Qena	11	14	19
Aswan	12	14	19
Average	7	9	13

Conclusion

Quantification of the impact of climate change on ET is very important for policy makers when developing future plans. This requires an accurate equation to calculate ET values. With only monthly maximum and minimum temperature measurements and solar radiation available, monthly ET can be calculated by H–S equation and then regressed on ET value previously calculated from P–M equation to develop calibration coefficients for each site. The above results showed that this method was accurate and the predicted ET values were close to the calculated ET values by P–M equation.

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