Optimizing irrigation requirements for almond trees grown in the South Sinai Governorate

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Abstract

South Sinai, Egypt is considered one of the most severe governorates for water scarcity. The current work aims to optimize irrigation requirements for almond trees (Prunus dulcis, syn. Prunus amygdalus, var. nonpareil) in the El-Tor area, South Sinai. Climate data of the El-Tor area was collected from 2010 to 2014 to calculate evapotranspiration. Two evapotranspiration equations were used in this work: Penman-Monteith (complex radiation equation) and Blaney-Criddle (simple temperature equation). Regression analysis was done between the two equations to determine their agreement and calculate a correction factor in order to make the Blaney-Criddle equation more accurate under South Sinai conditions (modified Blaney-Criddle). Irrigation requirements for one- to five-year-old almond trees in South Sinai were also calculated for the last five years. This study helps the almond farmers estimate the irrigation requirements by using maximum and minimum temperature (Blaney-Criddle) instead of using many climatic parameters (Penman-Monteith). The R2 regression analysis between the two tested equations was 0.95, which means that the suggested correction factor can be used with great confidence. Although there were significant differences between ETo values calculated using Penman-Monteith and Blaney-Criddle, there were no significant differences between the modified Blaney-Criddle (with the correction factor) and Penman-Monteith. This study recommends the use of the modified Blaney-Criddle equation for almond farmers who don't have access to the extensive climate data needed for Penman-Monteith, such as wind speed, relative humidity, sunshine hours and solar radiation. The output of this study is the accurate estimation of monthly irrigation requirements for almonds grown in South Sinai.

Introduction

Climate plays an important role in crop production. Crop growth periods, water requirements, and irrigation scheduling are all dependent on weather conditions. The useable agricultural land area is determined by climate and water availability. The Agro-climatic zone defines a land unit in terms of major climate characteristics, superimposed on the length of the growing period, i.e., moisture availability period (Food and Agriculture Organization (FAO), 1983). This classification is done using reference evapotranspiration data (ETo). The calculation of the ETo includes all the weather parameters relevant in a specific area. ETo is a combination of two processes: water evaporation from the soil surface and transpiration from the growing plants (Gardner et al., 1985).

Estimates of reference crop ETo rates are widely used in irrigation engineering to define crop water requirements. These estimates are used in the planning process for the development of irrigation schemes as well as to manage water distribution in existing schemes (Droogers & Al-

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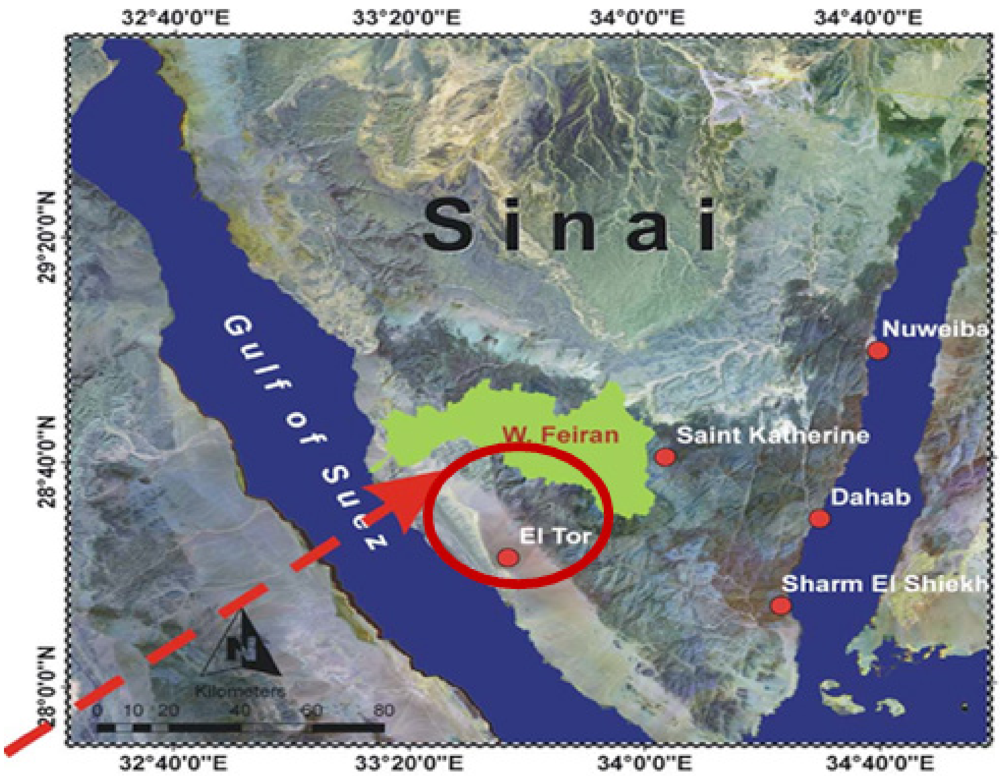

Figure 1: South Sinai, Egypt (left) and the research area (right) (Source: Omran et al. (2016))

len, 2002). Many models based on meteorological data have already been developed to estimate ETo in various climatic and geographic conditions. Among these models, Penman–Monteith FAO 56 (PM) was introduced as a standard model to estimate ETo (Allen et al., 1998). The major limitation of the PM model is that it requires many meteorological inputs, thereby limiting its utility in data-sparse areas. Therefore, the application of simpler models is recommended because they only need parameters that are readily available from station-observed meteorological data.

A large number of ETo formulas were developed from 1942 to 2005 to calculate crop water usage, starting with the development of the Blaney-Criddle (BC) formula and ending with the PM equation that became the American Society of Civil Engineers (ASCE) Standardized Reference ETo equation. The BC formula was first developed from soil moisture depletion, air temperature and humidity measurements in alfalfa, cotton, and deciduous trees in farmers' fields by Blaney and Criddle (1950) in the Pecos River, Roswell-Artesia area of New Mexico .

The almond tree (Prunus dulcis, synonym Prunus amygdalu, Family Rosaceae) is a small deciduous tree that grows to 20 to 30 feet naturally, but under cultivation is generally kept to 20 feet by pruning. The almond tree has an average life span of 20-25 years and does not bear fruit during the first 3-4 years after planting (Goldhammer & Fereres, 2004). El Afandi and Abdrabbo (2015) tested four ETo equations in different climatic regions and they mentioned that there were no statistically significant differences between the E-Pan and the PM model at $\alpha=0.05$, while the BC results differed significantly. The difference in percentage ratios between PM and BC was -13.3%. Hence, the PM equation has proven its capability in the estimation of reference ETo. The aim of the current study is to simplify the estimation of the irrigation requirement for almond trees in the South Sinai governorate by using a modified BC temperature equation with better accuracy.

Material and Methods

Climate data

The monthly data from 2010 to 2014 was collected from the automatic weather station of El Tor (latitude 28.23, longitude 32.61, altitude 21m) (**Figure 1**). The monthly data was averaged over the 5-year study period. The climate factors were temperature, wind speed, rain, relative humidity and radiation, which were all used in the estimation of ETo by the PM equation.

Evapotranspiration estimation models

ETo was calculated by applying the climate data to two models (PM and BC) in order to create a relationship between them.

Blaney-Criddle equation

The BC equation is as follows (Blaney, Hanson & Litz, 1950):

$ET_0 = p\ (0.46T_{mean} + 8)$

where T_{mean} = mean monthly temperature, calculated as Tmean [°C] = $(T_{max} + T_{min})/2$, and p = mean monthly percentage of maximum possible daytime hours of the year.

Penman- Monteith equation

The PM equation is calculated as follows (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)}$$

where ET_o is the daily reference evapotranspiration (mm day-1), Rn is the net radiation at the crop surface (MJ m-2 day-1), G is the soil heat flux density (MJ m-2 day-1), T is the mean daily air temperature at 2 m height (°C), U2 is the wind speed at 2 m height (m s-1), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the vapor pressure curve (kPa °C-1) and γ is the psychometric constant (kPa °C-1).

Irrigation requirement

The ETo is determined by the crop coefficient approach, whereby the effects of the various weather conditions are incorporated into ETo and the crop characteristics into the Kc coefficient. In the crop coefficient approach, the crop evapotranspiration, ETc, is calculated by multiplying the reference crop evapotranspiration, ETo, by a crop coefficient, Kc, according to the FAO (1983) and likewise adopted by Allen et al. (1998). Additional parameters can be added to the equation to deliver the irrigation requirement, as follows:

$IR = K_c * ET_o * LF * IE * R * Area /1000$

where IR = irrigation requirement (m^3 $feddan^{-1}$), Kc = crop coefficient, ET_o = reference crop evapotranspiration (mm day^{-1}), LF = leaching fraction (assumed 20% of irrigation water), IE = irrigation efficiency of the system in the field (assumed 90%), R =reduction factor, Area = the irrigated area (1 feddan = 0.42 ha), and dividing by 1000 achieves the conversion from liter to cubic meter.

Climate data

Table 1 shows the monthly weather data of the El-Tor governorate, South Sinai, averaged over the five-year period (2010-2014). The highest monthly average maximum air temperature was recorded during the summer

Table 1: Average monthly climatic data for El-Tor, South Sinai from 2010-2014

Month	Maximum temperature (°C)	Minimum temperature (°C)	Total precipitation (mm)	RH (%)	Wind (m/s)
Jan	20.78	20.78	0.7	52	2.02
Feb	22.02	22.02	1.5	53	1.51
Mar	24.66	24.66	0.0	51	1.97
Apr	29.74	29.74	0.0	45	2.58
May	32.72	32.72	0.1	43	2.89
Jun	35.58	35.58	0.0	45	2.94
Jul	35.52	35.52	0.0	62	2.89
Aug	36.06	36.06	7.4	63	2.94
Sep	34.02	34.02	14.4	55	1.31
Oct	32.22	32.22	0.0	53	0.90
Nov	25.84	25.84	0.2	59	1.15
Dec	21.64	21.64	32.2	51	1.15

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Table 2: Average estimated monthly evapotranspiration (ETo) by the Penman-Monteith and Blaney-Criddle equations for El-Tor, South Sinai from 2010-2014

Month	ET_o Blaney-Criddle (mm)	ET_o Penman- Monteith (mm)	Difference
Jan	3.4	2.8	-23%
Feb	3.7	3.5	-5%
Mar	4.4	5.1	15%
Apr	4.5	7.6	41%
May	5.2	9.3	44%
Jun	5.8	10.3	44%
Jul	5.6	9.4	40%
Aug	5.5	9.1	40%
Sep	4.9	6.0	18%
Oct	4.3	4.5	4%
Nov	3.6	3.0	-21%
Dec	3.2	2.2	-47%
Annual average	4.52	6.07	26%
P-Value	*	*	

* Significant

months (June, July and August), with a value around 36°C, while the lowest monthly average maximum air temperature was recorded during December, January and February, with a value around 22°C. The monthly average minimum temperature had the same trend as maximum air temperature. The highest monthly average minimum air temperature was around 22°C during June, July and August, while the lowest monthly average minimum air temperature was around 8.0°C during December, January and February. The highest monthly average relative humidity (RH) was recorded in July and August, with a value around 62%, while the lowest RH values were during May, with a value around 43%. The highest total monthly precipitation was recorded in December (32.2 mm), while there was no precipitation during March, April, June, July and October.

Statistical analysis

Statistical analysis was carried out using SAS software. A paired t–test was used to establish whether there were significant differences (α=0.05) between the ET_o values calculated using different equations (SAS, 2000).

Results and Discussions

Estimation of evapotranspiration for El-Tor

Data in **Table 2** shows the estimated monthly ETo by the PM and BC equations for El-Tor from 2010 to 2014. The highest ETo was estimated during June, July and August, while the lowest ETo was estimated during December and January for both tested equations. The BC results were higher than PM for November-February, while the PM equation gave higher values than BC from March to October. Paired t-tests revealed significant differences between the two equations. PM estimated higher annual ETo (6.07 mm) than BC (4.52 mm).

Regression between Penman-Monteith and Blaney-Criddle equations

Figure 2 shows the regression of estimated monthly ET_o calculated by the PM and BC equations for El-Tor from 2010 to 2014. Data indicate there is a strong positive relationship between ETo values calculated by the two equations, as indicated by the coefficient of determination (r^2=0.95). Using this regression equation, we can estimate ET_o calculated only from air temperature by implementing a modified BC equation with higher accuracy. The derived equation from this regression is as follows:

$$y = 0.1115*X^{2.5998}$$

where y is the ETo according to the modified BC model, 0.1115 is the correction factor, and x is the value of ET_o

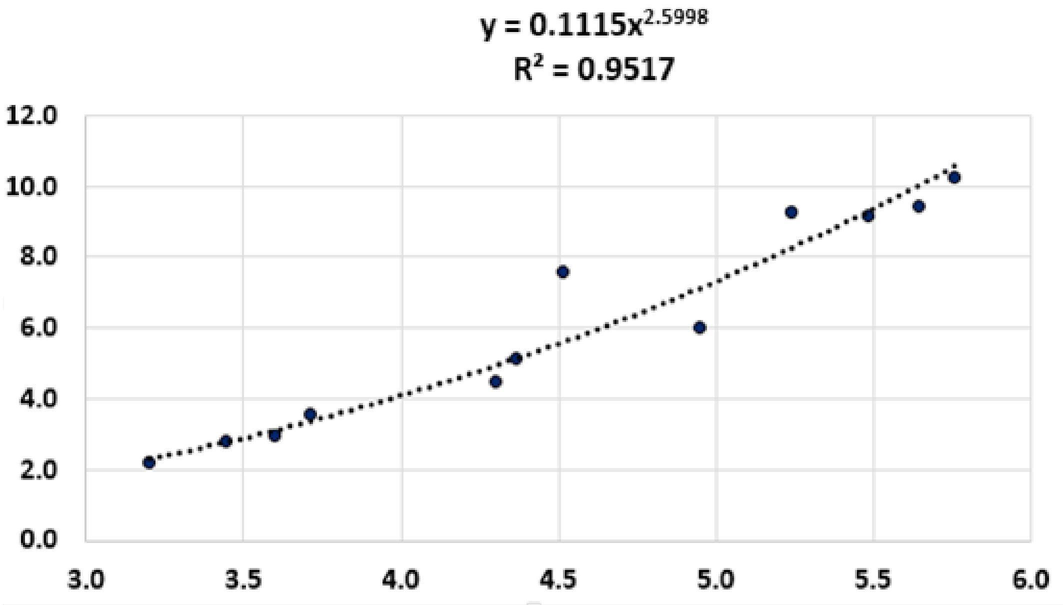

Figure 2: Regression analysis for estimated monthly evapotranspiration (ETo) by the Penman-Monteith and Blaney-Criddle equations for the El-Tor Governorate, South Sinai from 2010 to 2014

according to the original BC model.

Comparison between the modified Blaney–Criddle and Penman-Monteith equations

Data in Table 3 shows the estimated monthly ETo by PM and the modified BC equation for El-Tor Governorate, South Sinai from 2010 to 2014. The modified BC equation found higher values than PM from June-December, while the PM equation gave higher values than BC from January-May. There was no significant difference between the two tested equations using a paired t-test. The PM had higher annual ETo, with a monthly average of 6.07 mm, while the average for BC was 6.13 mm. The highest difference in percentage between the two equations was found during September (15.7%), while the lowest difference in percentage was during March (0.30%). These results agreed with the findings of Temesgen et al. (2005), who reported that the PM equation is considered a standard method compared to other empirical equations. In addition, Xu and Singh (2001; 2002) indicated that PM is the method which served as the basis for the development of the ET_o calculator software and is considered the most accurate method; therefore, PM is often used as a standard to verify other empirical methods (Allen et al., 2005). Due to the higher performance of PM, it has been accepted as the sole method for computing reference ET_o from meteorological data (Garcial, et al., 2006). The PM equation shows higher performance then the BC equation in different tested regions in Egypt. Therefore, one may conclude that PM could be used in estimation of the reference ET_o over different agro-climatic regions in Egypt with high performance compared to other methods (El-Afandi & Abdrabbo, 2015).

Irrigation Requirement for almond trees using estimated ET_o values

Data in **Table 4** show the estimated total monthly irrigation requirements by PM and the modified BC equation for El-Tor Governorate, South Sinai from 2010 to 2014. Total monthly water requirement had the lowest values during the winter season, from December to February. The irrigation requirement increased gradually from March to August, then sharply decreased from September to December. The highest water requirement was estimated during August for both tested ET_o equations. Water requirement under the modified BC was slightly higher than PM estimates, especially during the summer season (June-September). The lowest estimated annual irrigation requirement for almond trees was logically during the first year of growth, with a value of 728 and 742 mm for PM and the modified BC equation, respectively. Annual irrigation requirement increased gradually in the second year of tree growth, while the highest annual irrigation requirement for almond trees was estimated for the fifth year of growth. These results agree with the findings of Goldhamer, Viveros, and Salinas (2006), who mentioned that growers who are interested in reducing irrigation inputs because of water scarcity must determine how to allocate limited fresh water resources. While the studies identified to date quantified effects of the timing of water stress on production, none evaluated different stress timing strategies for applying the given amounts of seasonally available fresh water. In other words, the water application that results in the

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Table 3: Average estimated monthly evapotranspiration (ETo in mm /month) by the Penman-Monteith and modified Blaney-Criddle equations for El-Tor Governorate, South Sinai from 2010 to 2014

Month	ET_o Blaney-Criddle (mm)	ET_o Penman- Monteith (mm)	Difference
Jan	2.77	2.8	-0.8%
Feb	3.37	3.5	-5.1%
Mar	5.15	5.1	0.3%
Apr	6.61	7.6	-15.0%
May	8.27	9.3	-12.4%
Jun	10.57	10.3	2.7%
Jul	10.02	9.4	5.9%
Aug	9.31	9.1	1.7%
Sep	7.12	6.0	15.7%
Oct	4.94	4.5	9.6%
Nov	3.12	3.0	4.8%
Dec	2.29	2.2	5.0%
Annual average	6.13	6.07	1.0%
P-Value	*N.S.	*N.S	

*N.S Not significant

Table 4: Total monthly irrigation requirement (m3 feddan-1 month-1) for almond trees from the first to fifth year of life, estimated by the Penman-Monteith and modified Blaney-Criddle equations for the El-Tor Governorate, South Sinai from 2010 to 2014

	Penman-Monteith					Modified Blaney-Criddle				
	1st year	2nd year	3rd year	4th year	5th year	1st year	2nd year	3rd year	4th year	5th year
Jan	6.3	12.3	17.7	22.7	31.6	6.3	12.2	17.5	22.5	31.3
Feb	8.7	16.9	24.3	31.2	43.4	8.3	16.1	23.1	29.7	41.3
Mar	22.6	44.1	63.4	81.5	113.2	22.7	44.3	63.6	81.7	113.5
Apr	45.4	88.6	127.2	163.6	227.2	33.5	65.4	93.9	120.7	167.6
May	92.3	179.9	258.3	332.1	461.3	82.1	160.0	229.8	295.4	410.3
Jun	111.9	218.3	313.4	403.0	559.7	115.0	224.3	322.1	414.1	575.1
Jul	131.1	255.7	367.1	472.0	655.6	139.3	271.6	390.1	501.5	696.5
Aug	145.3	283.4	406.9	523.1	726.6	147.8	288.2	413.9	532.1	739.1
Sep	82.0	160.0	229.7	295.4	410.2	97.3	189.7	272.4	350.2	486.4
Oct	59.2	115.4	165.7	213.0	295.9	65.4	127.6	183.2	235.6	327.2
Nov	18.5	36.1	51.9	66.7	92.6	19.5	37.9	54.5	70.0	97.3
Dec	4.9	9.6	13.8	17.7	24.6	5.2	10.1	14.5	18.7	25.9
Total	**728**	**1420**	**2039**	**2622**	**3642**	**742**	**1448**	**2079**	**2672**	**3712**

most successful production system for a given fraction of the seasonal potential water needs has not been studied precisely. Moreover, accurate knowledge of water loss through crop evapotranspiration (ETc) is essential in order to avoid mistakes in estimating crop water needs, especially in areas suffering from water scarcity and drought. Deficiencies in the irrigation system are related to inappropriate irrigation estimations, which cause higher costs, wasted irrigation water, as well as negative environmental repercussions (Katerji & Rana, 2011). In arid and semi-arid areas, irrigation can be the main limiting factor in almond trees production (Hutmacher et al., 1994). In this context, the application of irrigation systems in rain-fed areas is considered an opportunity to improve the productivity of almond trees. In addition, Allen et al. (1998) reported that plants are exposed to a host of variables related to temperature which affect crop production, e.g., evaporation, transpiration, and vapor pressure deficit. Even solar radiation is related to the diurnal air temperature difference. Increasing air temperature leads to increased ET_o, depleting the soil of water, thus increasing the need for irrigation (Abdrabbo, Farag & El-Desokey, 2015; Farag, Abdrabbo, Ahmed, 2014). Furthermore, current Egyptian water policies are not made clear enough by the government. Research reflecting current policies may thus be particularly relevant in determining possible future steps. This is based on the 2005 Integrated Water Resources Management Plan and Water for the Future: National Water Resources Plan 2017, the latter of which was supported by the Dutch Government. In these documents, the stated major concerns are water for people, food production, industry, services, and employment; developing a strong institutional framework; quality, supply, and demand management; and protection and restoration of vital ecosystems (Farnum, 2014). These conditions demonstrate a vital need for accurate estimation of water requirements for different areas in Egypt in order to develop a better strategy for the future. Without appropriate water management, irrigated agriculture can be detrimental to the environment and endanger sustainability. Irrigated agriculture is facing growing competition for low-cost, high-quality water. In irrigated agriculture, water use efficiency is broader in scope than most other agronomic applications and must be considered on a watershed, basin, irrigation district, or catchment scale (Howell, 2001).

Conclusion

Under the semi-arid conditions of South Sinai, each water drop has a great value, not just in terms of agriculture, but for all aspects of life. Agricultural production that follows the deficit irrigation optimization strategy can contribute strongly to sustainable development and food security. The study results reveal that a modified Blaney-Criddle equation can estimate the irrigation requirements of almond trees under South Sinai conditions with simplicity and high accuracy compared to reference evapotranspiration rates calculated with the complex Penman-Monteith equation. The modified Blaney-Criddle equation uses only readily available climatic factors, namely maximum and minimum average monthly temperature, for estimating evapotranspiration. Therefore, agricultural extension associations, NGOs, and almond growers can use temperature data to estimate accurate irrigation requirements. Further studies are needed to investigate the effect of water deficit on the productivity of almond and quality of almond fruits. In addition, more research is needed related to water management for all cultivated crops in South Sinai alongside the impacts of implementing deficit irrigation in agricultural production.

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Conflict of Interests

The authors hereby declare that there is no conflict of interests.

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