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Estimation of Evapotranspiration of Citrus Tree from Climate Data for Groundwater Management in Saudi Arabia

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ABSTRACT

Water shortage for irrigation is a major problem in many arid and semiarid regions of the world. Saudi Arabia faces similar problem of water shortage for irrigation due to arid climatic conditions coupled with low rainfall and limited groundwater supplies to meet the growing need of water from crop and other field crop irrigation. In Saudi Arabia, citrus is frown as a cover crop in the date palm orchard and needed more water for sustainable fruit production. The main objective of this study was to estimate evapotranspiration of citrus from climatic data for different regions of Saudi Arabia and compare it with the evapotranspiration determined elsewhere for efficient management of citrus trees grown under arid climatic conditions. This study compared four different methods of calculating evapotranspiration (ET) of citrus tree with a standard method for seven different regions of Saudi Arabia. The mean daily estimated ET (mm day^{-1}) of citrus tree came to 1.83-8.66 (Hail), 2.14-8.26 (Kharaj), 2.45-7.23 (Taif), 1.61-7.73 (Qatif), 2.68-8.96 (Madinah), 2.14-8.10 (Hofuf) and 2.96-8.12 (Najran) regions of Saudi Arabia. The results showed definite differences in ET among the regions in Saudi Arabia. Also, ET_E values were significantly higher than those found in Arizona, USA. However, among the four methods, Blaney-Criddle gave the highest ET values and the radiation method gave the lowest values. Overall, the study findings provided an excellent potential of using meteorological data for estimating the ET of different fruit trees other than citrus under varying arid climatic regions.

Key words: Evapotranspiration, estimation, groundwater, pan-evaporation, solar radiation, temperature, Blaney-Criddle, Jensen-Haise

INTRODUCTION

Shortage of irrigation water is one of the major factors limiting the expansion of irrigated agriculture in the arid and semi-arid land of the world. Therefore, development of water-saving irrigation technology is considered to be one of the efficient ways to improve and develop sustainable agriculture in these regions. Knowledge of evapotranspiration is essential for efficient water management and demands precise measurements in order to determine irrigation water quantity and when to apply for higher water use efficiency. Unfortunately, data on measurements of evapotranspiration from mature fruit trees are not adequate. It is, therefore, imperative to determine the transpiration rate of different fruit trees not only for water allocation purposes but also for accurate irrigation water application. The estimation of evapotranspiration (ET) and its components (evaporation from the soil surface (Es) and transpiration or plant evaporation (E_p) has been a key issue in hydrological studies (Nakayama, 2011; Wagner *et al.*, 2011) and to enhance water use efficiency of irrigated crops (Evans and Sadler, 2008).

Many researchers used stress time, stress degree day, Crop Water Stress Index (CWSI) and stomatal conductance index approaches to estimate consumptive use of crops (Maes and Steppe, 2012). Castel (1997) determined the ET of a four year old Clementine citrus tree. The annual K_c values increased as the tree canopy grew and showed a good linear correlation with the percentage of ground cover. In another study, mean annual ET of tree was reported as 16,030 L tree^{-1} for March 1989-1990 and 11,733 L tree^{-1} for March 1990-1991 (Boman, 1994). ET rates were not significantly different among water-table treatments. Previously studies on evapotranspiration of citrus tree was estimated from soil water contents under flood irrigation or sprinkler irrigation (Smajstrla *et al.*, 1982; Castel *et al.*, 1987; Koo, 1961; Koo and Sites, 1955; Kalma and Stanhill, 1969). In addition to that, many researchers used this methodology to calculate ET of citrus and other fruit trees under low irrigation system (Sharples *et al.*, 1985; Sepaskhah and Kashefipour, 1995; Andreu *et al.*, 1997).

Evapotranspiration (ET) is basic for water resources planning and irrigation management. Many mathematical formulae have been developed to calculate ET using different climatic parameters (Penman, 1948; Blaney and Criddle, 1952; Jensen and Haise, 1963; Hargreaves, 1974; Rana *et al.*, 2005). However, it is well known that a method developed to estimate ET of crops for one area may not be valid for other areas. For example, Rogers and Bartholic (1976) used the Blaney-Criddle formula to estimate the annual ET for citrus trees at Lake Alfred, Florida USA and they calculated 1120 mm as compared to 1170 mm for Koo (1963). Whereas, Hashmi and Gerber (1967) used the formulation of Penman equation to calculate ET for an orange grove and found that computed ET was generally higher than the measured ET.

Presently available data on ET for citrus comes mostly from studies conducted in United States (Erie *et al.*, 1965; MacGillivray, 1975; Hoffman *et al.*, 1982). Weigand and Swanson (1982) reported that, depending on upon irrigation treatments, mean annual citrus water use at Weslaco ranged from 818-1191 mm for Ruby Red grapefruits, 686-1044 mm for Marrs oranges and 846-1232 mm for Valencia orange over the period from 1969-1975.

In Saudi Arabia, citrus is grown on over more than 5000 h and produces more than 40000 t per year (Central Department of Statistics, 1984). Currently, there is no reliable ET data for irrigation scheduling of citrus orchard in Saudi Arabia or other similar arid regions. This study used different methods to estimate ET of citrus using local climate data from citrus growing regions in Saudi Arabia and provide useable guidelines for irrigation scheduling by comparing the various ET calculations.

MATERIALS AND METHODS

Evapotranspiration (ET) was estimated from four equations using different climatological data as input. The procedures for three of these equations namely Pan-evaporation, Radiation and Blaney-Criddle were taken from Doorenbos and Pruitt (1975). While the procedure for Jensen-Haise equation was taken from Jensen (1973). The mean monthly climatological data required for different equations was taken from Hydrology Section, Ministry of Water and Electricity, Saudi Arabia (personnel communications) and presented in Table 1. However, the values of different coefficients used to estimate ET were taken directly from the literature for citrus orchards without weed control. The various equations used in the study are summarized below.

Pan-evaporation: Evapotranspiration (ET) can be calculated from the Eq. 1 as below:

$$ET = K_c. K_p. K_{pan} \tag{1}$$

Table 1: Meteorological data used for estimating evapotranspiration of citrus tree

Months	Hail	Qatif	Najran	Hofuf	Taif	Al-Madinah	Kharj	Arizona, USA
Pan-evaporation (mm day^{-1})								
January	5.11	2.92	6.07	4.39	4.84	5.88	4.58	2.8
February	5.96	3.82	5.56	5.78	5.40	7.77	5.76	4.0
March	7.77	4.84	7.64	6.39	7.80	10.23	7.16	5.3
April	9.53	7.26	8.57	9.41	8.46	12.42	10.24	7.7
May	14.05	9.18	10.98	11.95	9.44	15.81	12.83	9.5
June	17.03	12.95	11.30	14.43	12.25	18.93	16.31	11.4
July	18.17	12.24	10.76	13.62	13.69	18.56	16.71	11.2
August	17.84	11.76	11.07	11.85	13.46	17.22	15.51	10.3
September	15.05	8.61	9.00	9.53	12.02	15.30	12.11	8.1
October	10.90	6.01	8.27	7.53	7.87	10.73	8.54	5.5
November	7.81	4.32	6.21	5.17	5.86	6.72	5.93	4.0
December	5.61	3.45	4.98	3.73	5.19	5.28	4.25	2.8
Mean air-temperature (°C)								
January	10.60	14.97	16.43	14.23	14.97	17.63	15.20	10.4
February	1.07	15.90	18.37	15.33	14.17	18.00	16.37	12.9
March	15.37	20.23	21.07	19.33	17.60	21.37	21.00	15.5
April	20.83	24.67	24.63	24.43	20.70	26.83	26.40	18.2
May	26.33	31.37	27.03	30.00	23.90	30.93	32.13	23.1
June	30.10	33.73	27.90	33.93	27.57	34.37	34.37	28.4
July	31.37	35.13	29.67	34.03	28.40	34.60	35.43	31.5
August	30.77	34.20	29.77	33.97	27.90	35.13	34.43	30.9
September	29.17	32.23	25.07	30.73	25.43	32.73	31.57	27.9
October	24.03	27.80	20.43	25.73	21.00	28.57	26.37	22.1
November	16.67	21.40	17.03	19.90	17.40	22.23	20.23	14.7
December	12.30	16.67	14.90	15.53	15.13	18.97	15.27	10.3
Solar radiation (mm day^{-1})								
January	4.70	3.43	-	5.75	6.16	5.50	5.40	4.6
February	5.93	4.67	-	7.25	7.33	6.63	6.31	6.2
March	6.91	5.47	-	6.68	8.43	7.56	6.71	7.9
April	7.67	7.32	-	9.03	8.46	8.39	7.85	10.5
May	8.07	7.84	-	9.08	8.75	8.81	7.90	11.4
June	9.12	9.12	-	9.69	9.28	9.34	8.92	11.8
July	9.22	8.61	-	9.75	9.49	9.41	8.76	10.5
August	8.61	7.07	-	9.41	8.90	8.71	8.20	10.3
September	7.57	6.76	-	9.43	8.66	8.06	7.80	8.0
October	6.41	5.27	-	8.03	7.66	6.87	6.69	6.9
November	5.41	3.86	-	7.02	6.69	5.95	5.88	5.4
December	4.77	3.09	-	6.52	6.27	5.28	5.37	4.2

where, K_c is the crop coefficient, K_p is the pan-coefficient and E_{pan} is the pan-evaporation. The mean daily rate of evaporation from a Class A pan on a monthly basis from 1990-1995 for seven different regions of Saudi Arabia is presented in Table 1. The values of Kc, are directly taken from Doorenbos and Pruitt (1975) for the large mature orange trees. The Pan coefficient based on the wind speed (less than 10 km day^{-1}), humidity (mean daily humidity between 40-70%). Pan location (10 m of fallow dry soil upwind from the pan) is 0.7 (Doorenbos and Pruitt, 1975).

Radiation: Evapotranspiration (ET) can be calculated from the Eq. 2 as below:

$$ET = K_c(-0.3+0.84\ WRs) \quad (2)$$

where, W is a weighing factor which depends on temperature and altitude and R_s is the solar radiation converted to an equivalent depth of evaporation of evaporation in mm day^{-1}. The numerical coefficient are based on a moderate relative humidity and light daytime wind.

Jensen-haise: Evapotranspiration (ET) can be calculated from the Eq. 3 as below:

$$ET = K_C.\ C_T.\ (T\text{-}T_x)R_s \tag{3}$$

where, C_T and T_x are coefficients which depends on humidity, temperature and duration. For this study, C_T was taken as 0.223 and T_x was taken as 3.4°C. The T is the mean of daily maximum and minimum temperature.

Blaney-criddle: The Blaney-criddel approach accounts for low daytime humidity, light daytime wind and a high rate of actual to maximum possible sunshine hours. It estimates the evapotranspiration (ET) by the following relationship:

$$ET = K_C\ (-2.60+1.55f) \tag{4}$$

where, f is given by the following Eq. 5 as:

$$f = p\ (0.46T+8.13) \tag{5}$$

and where p is the mean daily percentage of daytime hours for a given month and latitude.

Data analysis: The study data were analyzed by regression and ANOVA statistical techniques according to SAS Institute Inc. (SAS., 2010).

RESULTS AND DISCUSSION

Estimated evapotranspiration (ET_E): The mean daily estimated ET (mm day^{-1}) of citrus tree came to 1.83-8.66 (Hail), 2.14-8.26 (Kharaj), 2.45-7.23 (Taif), 1.61-7.73 (Qatif), 2.68-8.96 (Madinah), 2.14-8.10 (Hofuf) and 2.96-8.12 (Najran) as given in Table 2. The results showed significantly higher ET for citrus than that obtained in Arizona, USA. Whereas, the difference in ET_E among Hofuf, Hail and Al-Kharj regions was insignificant. The highest ET_E was found for Al-Madinah farm followed by Najran region. The lowest ET_E for citrus was observed for Taif and Qatif regions which agreed with the findings of Hoffman *et al.* (1982).

Although, there was relatively large difference in ET values, the regression analysis showed a close relationship between the ET of citrus estimated in Arizona (USA) with that estimated from local climate data for different citrus growing regions in Saudi Arabia. The regression coefficients (r) ranged from 0.955-0.992 for the estimated and from 0.959-0.993 for the experimentally determined ET values (Table 3). This also suggests that ET for citrus can be estimated from the local climate data providing reasonably good estimate in the absence of on-site experimentally determined ET for citrus. Similar findings were reported by many researchers (Doorenbos and Pruitt, 1977; Yang *et al.*, 2002a, b; Pereira *et al.*, 2006; Villalobos *et al.*, 2013) who pointed out that ET of young citrus orchards can also be estimated if K_C (crop coefficient) values of young citrus trees are used. They further reported that Evapotranspiration under saline irrigation (ET_s) can be

Table 2: Mean evapotranspiration values (mm day^{-1}) for mature citrus trees based on four estimation equations

Months	Hail	Qatif	Najran	Hofuf	Taif	Madinah	Kharaj	Arizona, USA
January	1.83	1.61	3.46	2.14	2.45	2.68	2.14	1.40
February	2.31	2.15	2.96	2.79	2.80	3.28	2.61	2.10
March	3.39	2.74	4.39	3.11	4.03	4.48	3.39	3.10
April	4.44	4.01	5.50	4.80	4.45	5.70	4.74	4.30
May	5.93	5.11	6.91	6.09	5.06	6.96	6.32	5.50
June	8.22	7.73	8.12	8.10	6.46	8.96	8.00	7.00
July	8.66	7.58	6.74	7.93	7.23	8.95	8.26	6.80
August	8.12	6.76	7.44	7.57	6.80	8.51	7.71	6.50
September	6.66	5.89	6.85	6.69	6.06	7.32	6.51	5.00
October	5.08	4.26	5.79	5.20	4.61	5.66	4.92	3.50
November	3.04	2.54	4.01	3.22	3.20	3.61	3.15	2.10
December	2.12	1.82	3.34	2.55	2.68	2.82	2.27	1.40
Mean	4.98	4.35	5.46	5.02	4.65	5.74	5.00	4.06
Annual (mm)	1824	1592	1997	1835	1702	2101	1830	1480

Table 3: Comparison between estimated and observed evapotranspiration of mature orange tree calculated at Arizona (USA) and Saudi Arabia

Areas	Regression equation	$\hat{y}$	r
Hail	1: Y = 1.174X+0.218	1.597	0.978
	2: Y = 0.972X+1.094	2.040	0.988
Hofuf	1: Y = 1.040X+0.791	1.875	0.977
	2: Y = 0.857X+1.588	2.323	0.981
Kharaj	1: Y = 1.087X+0.589	1.771	0.987
	2: Y = 0.894X+1.427	2.225	0.991
Taif	1: Y = 0.782X+1.479	2.090	0.969
	2: Y = 0.653X+2.040	2.467	0.988
Qatif	1: Y = 1.050X+0.088	1.191	0.980
	2: Y = 0.861X+0.906	1.647	0.980
Madinah	1: Y = 1.129X+1.162	2.437	0.992
	2: Y = 0.926X+2.040	2.898	0.993
Najran	1: Y = 0.812X+2.166	2.820	0.955
	2: Y = 0.667X+2.791	3.236	0.959

Y: ET (citrus) for different regions, X: ET (citrus) calculated at Arizona, USA, $\hat{y}$: A linear estimate of Y for a given X value, r: Correlation coefficient, 1: Estimated vs. estimated calculations, 2: Experimental vs. estimated values

calculated from evapotranspiration under freshwater irrigation (ET) by the equation $ET_s = K_s$-ET. Also, K_s can be expressed as a function of critical soil-water electrical conductivity (EC_{sw}).

Comparison of ET_E among different regions: A comparison of ET_E among the different regions highlighted the significance of climate variability on ET estimation. It was found that ET_E was significantly higher in relatively hotter regions as compared to the cooler regions (Table 2). This variation in ET_E may be due to the difference in mean air-temperature, solar radiation, relative humidity, day light hours and pan-evaporation. Besides, rainfall in the region might have some impact on ET_E value, though it was not considered in the calculations. Similar results were reported by Villalobos *et al.* (2013) who applied radiation use efficiency and CO_2 assimilation to estimate the ET of different fruit trees in Spain and California, USA. They further calculated the transpiration coefficient (K_t) as the ratio of measured E_p to the reference evapotranspiration for all the species.

Table 4: Comparison of methods used to estimate evapotranspiration of citrus (annual mean ET = mm day^{-1})

Methods	Hofuf	Qatif	Madinah	Taif	Najran	Hail	Kharaj
Blaney-Criddle	7.190	7.110	8.520	6.530	6.320	7.110	7.210
Pan-evaporation	4.830	4.110	6.760	4.920	4.590	6.240	6.630
Jensen-Haise	4.390	3.470	4.330	3.690	-	3.430	3.980
Radiation	3.650	2.710	3.370	3.540	-	3.150	3.180
Mean	5.010	4.350	5.740	4.670	5.460	4.980	5.000
LSD (0.05%)	1.298	1.410	1.645	1.307	0.941	1.703	1.570
Standard deviation	1.526	1.926	2.338	1.384	1.226	1.989	1.790

Table 5: Irrigation schedule for mature citrus trees in different regions of Saudi Arabia

	Irrigation interval (days)						
Months	Hofuf	Qatif	Taif	Hail	Najran	Kharaj	Madinah farm
January	8	9	7	9	5	8	6
February	7	8	6	8	6	7	5
March	5	6	4	6	4	5	4
April	4	4	4	4	3	4	3
May	3	3	4	3	2	3	2
June	2	2	3	2	2	2	2
July	2	2	2	2	2	2	2
August	2	3	3	2	2	2	2
September	3	3	3	3	2	3	2
October	4	4	4	4	3	4	3
November	6	7	6	6	5	7	5
December	8	10	7	9	5	9	7

Assumptions for the given irrigation schedule, Soil type: Loam, Field capacity: 16%, Permanent wilting point: 7%, Irrigation system: Drip system, Dripper discharge: 1.5 L min^{-1}, Fixed irrigation time: 2 h, Dripper per tree: 1, Irrigation efficiency: 80%

Comparison of estimation methods: The results in Table 4 show that among the different ET estimation methods, Blaney-Criddle method estimated significantly higher ET_E for citrus whereas the radiation method gave significantly lower ET_E values. The remaining two methods (pan-evaporation and Jensen-Haise) were in between the above two methods in estimating the ET for citrus. The results also showed that ET_E values calculated by pan-evaporation method are in close agreement with the experimentally determined ET_P for citrus according to Hoffman *et al.* (1982). This may be attributed to the overall cumulative effect of climate parameters on water evaporation as the water is not a limiting factor. Moreover, the wide variability in ET_E may be due to the use of different climate parameters in different predictive methods. Therefore, this variability in ET_E suggests that a degree of caution should be exercised while using the results.

Proposed irrigation schedule: A reference irrigation schedule is provided as a guide for use in different citrus growing regions in Saudi Arabia (Table 5). The references irrigation schedule given in Table 5 was made utilizing a modified CIMIS irrigation scheduling program (Alajaji *et al.*, 1987). The program uses the estimated ET of citrus (Table 2) assuming that (1) The soil type is loam with a field capacity and permanent wilting point of 16 and 7% by weight, respectively, (2) The soil bulk density is 1.55 g cm^{-3}, (3) The irrigation system is automatic drip system with a discharge rate of 1.5 L min^{-1} per dripper, (4) Each tree has only one dripper for supplying irrigation water, (5) The irrigation time is fixed as two hours per irrigation and (6) The irrigation efficiency is considered as

80%. It is further pointed out that the irrigation interval in days in Table 5 is the time from stopping one irrigation until starting the next irrigation. These ET estimations for citrus tree are climate dependent and may fall between the highest (Erie *et al.*, 1965) and the lowest (Rogers *et al.*, 1983; MacGillivray, 1975) values derived from other methods.

CONCLUSION

The ET_E values of citrus calculated from four different predictive methods is generally higher than ET values determined experimentally at Arizona, USA probably as the climate in Saudi Arabia is more arid than other regions in the world. The results showed that ET_E of citrus calculated from two predictive methods namely pan-evaporation and Jensen-Haise is in close agreement with experimentally determined by Hoffman *et al.* (1982). Since no ET measurements are available locally for comparison, the ET of citrus calculated by Hoffman *et al.* (1982) was taken as reference values. However, the remaining two estimation methods i.e., Blaney-Criddle predicted significantly higher ET and the radiation method significantly lower ET values for citrus. The results in this study indicate that local climatic data can be used in estimating ET of citrus trees. This investigation, though theoretical, showed that several methods may be used to estimate ET for citrus orchards till the actual ET measurements are carried out in different climatic regions in Saudi Arabia. Overall, the four methods used provided reasonable results and will at least maximize the water use efficiency in citrus growing regions by giving farmers approximate guidelines to set up an irrigation schedule for good on-farm water management.

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