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Evapotranspiration models assessment under hyper-arid environment

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Abstract In this study, we develop more accurate hyper-arid evapotranspiration (ET) models to help improve irrigation water conservation. We examine five ET models (one combination model, three radiation-based models, and one temperature-based model) under hyper-arid condition at three center-pivot fields in the Kingdom of Saudi Arabia. These models were evaluated and calibrated for the alfalfa crop of 2010 and validated for the wheat and potato crops of 2011. The FAO-56 Penman–Monteith (PM) was the most accurate ET model for estimating crop water irrigation needs. The Turc and the Makkink solar radiation-based ET models provided the least accurate estimates even after calibration, while the calibrated Hargreaves–Samani temperature-based model provided the second most accurate estimates for irrigation scheduling in hyper-arid environments. Unlike the FAO-56 PM model, Hargreaves–Samani does not require wind speed or relative humidity data. The most sensitive parameter for this model is air temperature, which is readily available at most sites. The Priestley–Taylor model is highly sensitive to solar radiation data that may not be locally available. The main drawback of the FAO-56 PM model is that it requires extensive list of meteorological data. Weather forecasts are often limited to air temperature data that limit the use of the FAO-56 PM model for irrigation scheduling compared to the calibrated Hargreaves–Samani model.

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Introduction

Saudi Arabia has limited water resources. There are no permanent freshwater lakes or rivers, and the total groundwater resources are estimated to be approximately 500 km^3. Less than half of this volume meets the standards for drinking water (FAO 2008). While Al-Mogrin (2001) estimated the available groundwater to be 2175 km^3, the Ministry of Planning reported a more conservative estimate of only 338 km^3 (FAO 2008). Regardless, there is no doubt that Saudi Arabia has limited nonrenewable groundwater resources. Water usage is primarily agricultural, with 88 % used for that purpose, while municipal and industrial usage accounts for only 9 and 3 %, respectively (Abderrahman 2001; Al-Ghobari 2000; Alazba et al. 2003). Approximately, 97 % of the water used for agricultural activities comes from nonrenewable groundwater resources (FAO 2008). Obviously, agriculture plays a major role in water consumption, as is the case in most developing countries.

As a consequence of agriculture, irrigation expansion, and improper irrigation water management, the groundwater is being depleted at an extremely fast rate. For example, when the Saudi Agriculture Development Company was established in 1983, the static groundwater level in the Wadi Al-Dawasir aquifer was 76 m. At present, it is at 194 m (an over 4 m per year drop in the groundwater level). This illustrates that Saudi Arabia is facing a water crisis due in part to improper water management, not only in Wadi Al-Dawasir but also in other regions of the country. As a result, the government of Saudi

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Arabia has introduced benchmarking water consumption in addition to incentive programs designed to encourage agricultural companies to adopt water conservation policies. However, one of the most important factors for water resource planning and irrigation scheduling is the determination of crop evapotranspiration (Alazba et al. 2003).

Evapotranspiration (ET) can be measured directly or indirectly using a number of methods such as using lysimeters or monitoring the change in soil water storage. Methods for measuring ET are generally considered complicated and time consuming. Thus, the use of ET models is inevitable as data is required regardless of the measurement capabilities (Farahani et al. 2007). A large number of ET models have been developed, including those of Penman (1948), Thornthwaite (1948), Makkink (1957), Turc (1961), and Priestley and Taylor (1972). Some of the ET estimation models were derived using field experiments while others are theoretically based (Jensen et al. 1990). Several of these models involve the use of meteorological data that may not be widely available in developing countries. Parameters such as solar radiation, relative humidity, and wind speed are often unavailable, thus making it necessary to use simpler models based on the available meteorological data.

Previous studies in Saudi Arabia regarding performance evaluation and ranking of ET models have been inconclusive. For instance, Alazba et al. (2003) and Ismail (1993) found that the model by Jensen and Haise (1963) was the best model for estimating ET, while Al-Omran et al. (2004) and Mohammad (1997) concluded the Penman family model obtained the most accurate results. It must also be noted that FAO-56 Penman–Monteith (ET) model—recommended by the Food and Agriculture Organization (FAO)—has recently gained popularity in Saudi Arabia (ElNesr and Alazba 2010; ElNesr et al. 2011). The main objective of this study is to calibrate and evaluate select ET models (FAO-56 Penman–Monteith (PM), Hargreaves–Samani, Priestley–Taylor, Makkink, and Turc) in the hyper-arid environment of Saudi Arabia at the field level for alfalfa, wheat, and potato crops.

Materials and methods

Site description

Experimental data collected from January 2010 to March 2011 was obtained from the Saudi Agricultural Development Company (SADCo.) and the Leha Company. The study area lies between latitude 19° 56′ 05.14″ N to 20° 00′ 30.63″ N and longitude 44° 45′ 54.60″ E to 44° 51′ 58.07″ E at an elevation of 770 m above the mean sea level (Fig. 1).

In addition to the INMA weather station located within the project site, the two closest reliable weather stations—located about 30 km northeast of the study area—included Wadi Al-Dawasir airport and the National Agriculture Development Company (NADEC) weather stations. The weather data included daily values of the following parameters: maximum, minimum, and average air temperature; humidity; average and high wind speed; atmospheric pressure; precipitation; and solar radiation. As shown in Figs. 2 and 3, in Saudi Arabia, the peak of solar radiation occurs on Julian day 173 while the peak air temperature occurs 1 month later on Julian day 203.

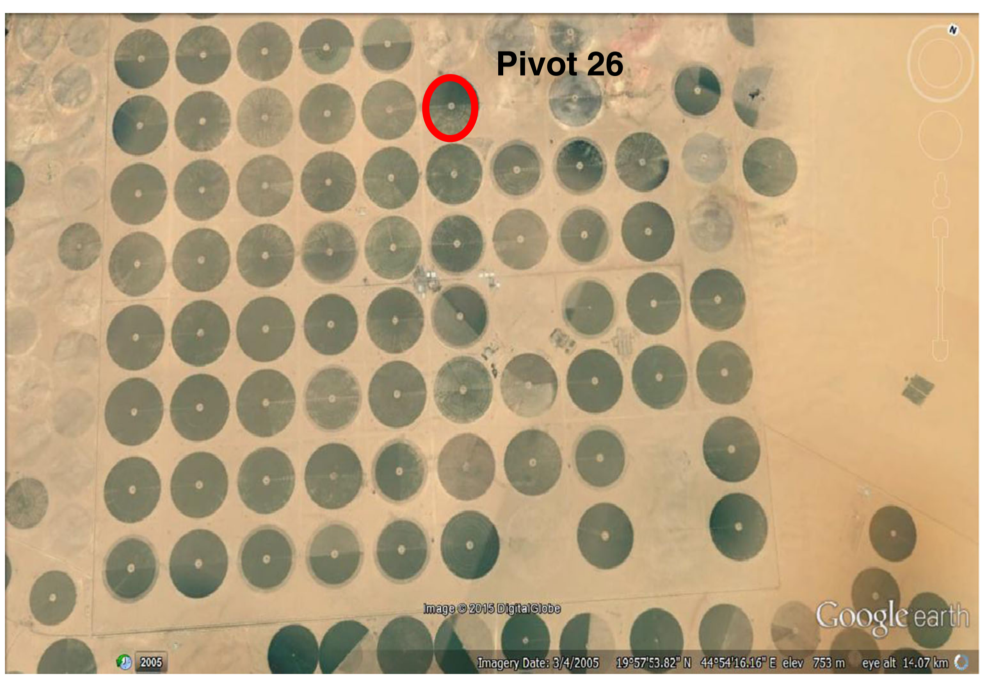

Fig. 1 A satellite image of the INMA; pivot no. 26 is circled

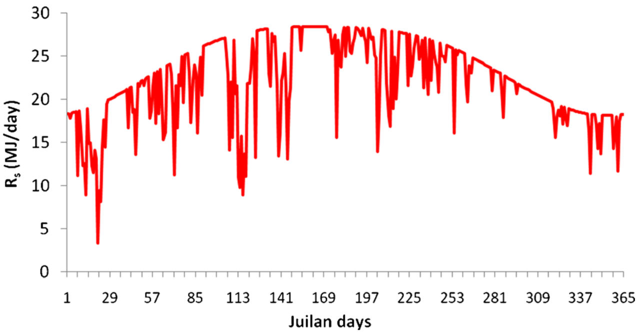

Fig. 2 Measured solar radiation (R_s) at INMA station in 2010

Fig. 4 The EnviroSCAN multilevel soil moisture sensor at pivot no. 26

Three crops (alfalfa, wheat, and potato) were selected for this study. These crops were irrigated by centre pivots, which cover areas of 60, 66, and 45 ha for alfalfa, wheat, and potato, respectively. The irrigation water volumes were measured using an ultrasonic flow meter and recorded on a monthly basis. The EnviroSCAN system was chosen to monitor soil water content continuously at various depths within the crop root zone. The EnviroSCAN system determines how often and how much to irrigate. The EnviroSCAN soil moisture profile monitoring system (Figs. 4 and 5) was used to measure the soil water content at various depths, which is one of the components required to calculate the water balance. The EnviroSCAN capacitance probes have multiple sensors located at various depths at 10-cm intervals. Each probe can hold up to 16 sensors. The probe contained five sensors at depths of 10, 20, 30, 50, and 80 cm for alfalfa and five sensors at depths of 10, 20, 30, 40, and 50 cm for wheat and potato.

The probes were connected to a solar powered data logger, and the sensors gave readings for soil moisture at 30-min intervals. The dielectric content of the soil is measured using the capacitance method, which reflects the water content of the soil-water-air mixture.

Model description

Water balance model

The root zone water mass balance of the alfalfa, wheat, and potato grown in sandy loam soil can be defined based on the conservation of mass equation as follows:

$$\Delta S = I_{\mathrm{net}} + P_{\mathrm{eff}} + D_{\mathrm{p}} + ET \quad (1)$$

where ΔS is the change in water storage in the root zone, P_{eff} is the effective precipitation, I_{net} is the net irrigation water, D_{p} is the drainage water below the bottom of the root zone, and ET is the ET during a given period of time, Δt=1 week. All of these variables are expressed in millimeters. A runoff component was not considered in Eq. (1) as the field was leveled to a zero slope, and the irrigation application rate was considerably less than the saturated hydraulic conductivity of the soil (Zhang et al. 2004). Effective precipitation is also considered negligible as the rainfall that occurred during the cutting and bailing period did not exceed 5.4 mm/year.

The variation in soil water storage between two depths (z_1= 0 cm and z_2=80 cm) for alfalfa and (z_1=0 cm and z_2=50 cm) for wheat and potato for a given period of time Δt=30 min was calculated based on measured water content readings by the capacitance probes using Eq. (2):

$$\Delta s = \int_{z_1}^{z_2} \theta(z, t_1)dz - \int_{z_1}^{z_2} \theta(z, t_2)dz \quad (2)$$

where Δs is the change in soil water content θ in (mm), z_1 and z_2 are depth in (cm), and t_1 and t_2 are the time calculation at 30-min intervals. Data from the deepest sensor confirmed the prediction that there was barely any deep percolation below the root zone for all three crops of alfalfa, wheat, and potato.

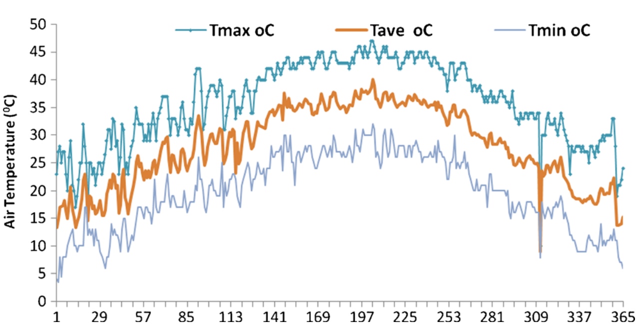

Fig. 3 Measured air temperature at INMA station in 2010

Reference ET model description

Five models were used in this research for the estimation of reference crop ET, including: FAO-56 PM, Hargreaves–Samani, Priestley–Taylor, Makkink, and Turc. Each model depends on a different set of meteorological variables.

FAO-56 Penman–Monteith (PM)

The Penman family models are generally considered to be among the most accurate ET models in any climate. The

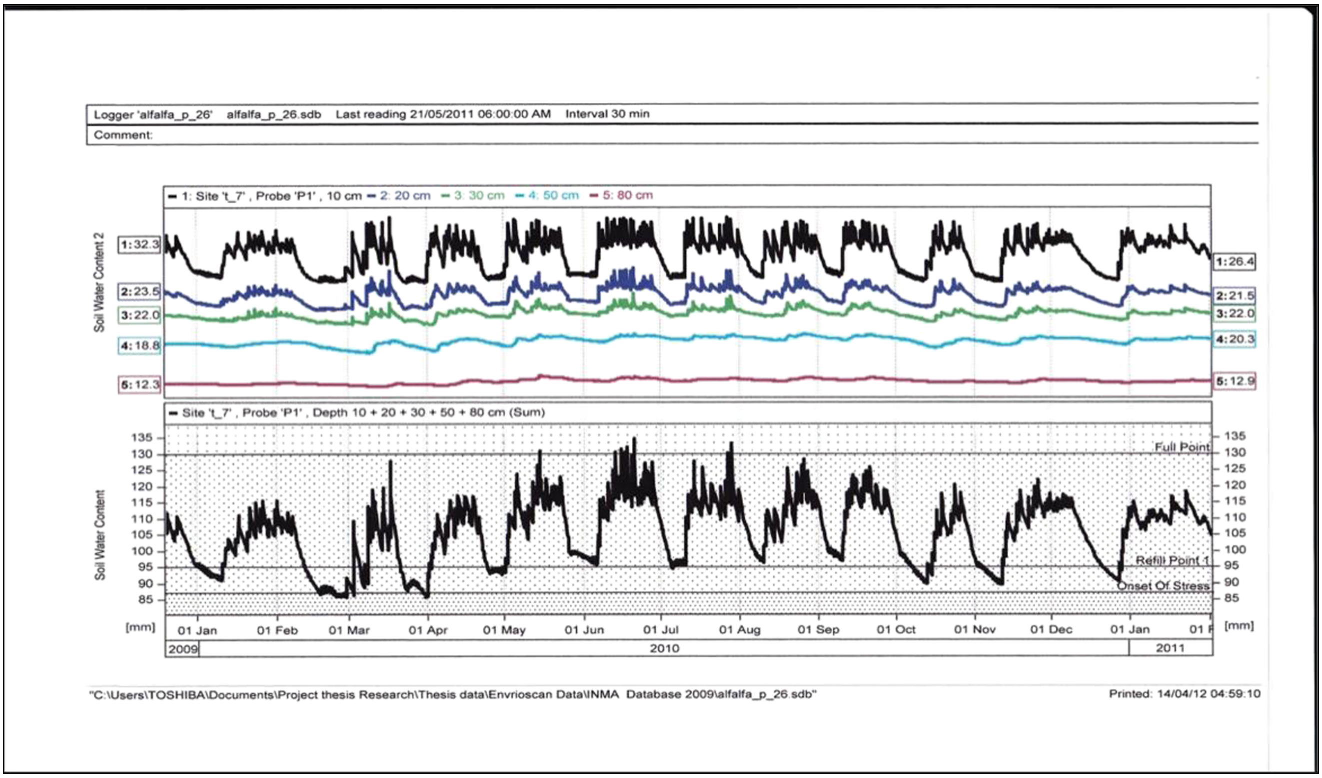

Fig. 5 Alfalfa EnviroSCAN soil water content at various depths

FAO-56 PM equation, specifically, was derived from the original Penman–Monteith equation and surface and aerodynamic resistance equations (Dinpashoh et al. 2011). According to Allen et al. (1998) the FAO-56 PM equation, for a grass reference crop is defined as follows:

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \dfrac{900\,\gamma\,u_2\,(e_s - e_a)}{T + 273}}{\Delta + \gamma\,(1 + 0.34\,u_2)} \quad (3)$$

where ET_0 is the reference ET (mm/day), R_n is the net radiation at the canopy surface (MJ/m^2/day) (calculated as the sum of the net short wave and net long wave radiation) (Todorovic et al. 2013), G is the soil heat flux at the soil surface (MJ/m^2/day), γ is the psychometric constant (kPa/°C), T is the mean daily temperature (°C), u_2 is the mean daily wind speed at 2-m height (m/s), e_s is the mean saturation vapor pressure (kPa), e_a is the mean actual vapor pressure (kPa), ($e_s - e_a$) is the saturation vapor pressure deficit (kPa), and Δ is the slope of the saturation vapor-pressure-temperature.

Hargreaves–Samani (HS)

The Hargreaves–Samani model (1985) is a modified version of the older ET model presented by Hargreaves and Allen (2003):

$$ET_0 = 0.0023 R_a (T_{ave} + 17.8)(T_{max} - T_{min})^{0.5} \quad (4)$$

where T_{ave} is the mean daily air temperature (°C), T_{max} is the maximum daily temperature (°C), T_{min} is the minimum daily temperature (°C), and R_a is the daily extraterrestrial radiation (mm/day).

Priestley–Taylor (PT)

The Priestley–Taylor method (1972) is a shortened version of the original Penman model. The model was intended for use in large-scale numerical modeling, where it is assumed that advection is small, allowing the aerodynamic component of the original Penman equation to be reduced to a coefficient. The form of PT used in this study is described as follows by (Jensen et al. 1990):

$$ET_0 = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (5)$$

where α is the empirical coefficient =1.26, γ is the psychometric constant (kPa/°C), R_n is the net radiation (MJ/m^2/day), and G is the soil heat flux (MJ/m^2/day).

Makkink (MK)

The Makkink model was designed in 1957 to estimate potential ET. This model was modified from the Penman model:

$$ET_0 = 0.61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{\lambda} - 0.12 \quad (6)$$

where R_s is solar radiation (MJ/m^2/day), γ is the psychometric constant kPa/°C), and λ is the latent heat of vaporization (MJ/kg).

Turc (TR)

The Turc model (1961) was developed Western Europe. It has been used to some extent in the USA (e.g., Amatya et al. 1995), as defined for operational use by Allen (2008):

$$ET_0 = \frac{a_T \; 0.013 \; T_{ave} \; (23.8856 \, R_s \; + \; 50)}{\lambda \, (T_{ave} \; + \; 15)} \tag{7}$$

where ET_0 is the reference crop evapotranspiration (mm/day), T_{mean} is the mean monthly air temperature (°C), R_s is the solar radiation (MJ/m^2/day), and λ is the latent heat of vaporization (MJ/kg). If the average relative humidity is greater than 50 %, then a_T=1; if not, then it can be calculated by $a_T = 1 + \frac{50 - RH_{ave}}{70}$

Single crop coefficient (K_c)

The single alfalfa, wheat, and potato crop coefficients were taken from the FAO-published book to compute crop ET. There are four stages developed for each cut, as alfalfa is treated as a full crop similar to wheat and potato, starting from irrigation until the crop is harvested.

As all variables were calculated, the crop ET can be calculated using the following equation:

$$ET_c = ET_o \cdot K_c \tag{8}$$

where ET_c is the crop ET (mm), ET_o is the reference ET (mm), and K_c is the crop coefficient (dimensionless unit).

Model calibration and evaluation

Figure 6 shows a fairly good linear correlation between the measured and the five ET model estimates for the alfalfa crop in 2010. The five ET models of PM, HS, PT, MK, and TR were calibrated using a correction factor and by minimizing the sum of the square errors of the calculated models versus observed daily ET data for the 2010 alfalfa crop. The correction factors for the PM, HS, PT, MK, and TR were 1.00, 1.26, 1.58, 1.57, and 2.62, respectively.

The accuracy of the calibrated ET models (see Fig. 7) was then tested for the wheat and potato crops. The ET model performance evaluations and model rankings were done by comparison of the coefficient of determination (R^2), the Nash–Sutcliffe coefficient of efficiency (E) and its modified version (E_1), the root mean square error (RMSE), and the coefficient of residual mass (CRM) as presented in Table 1.

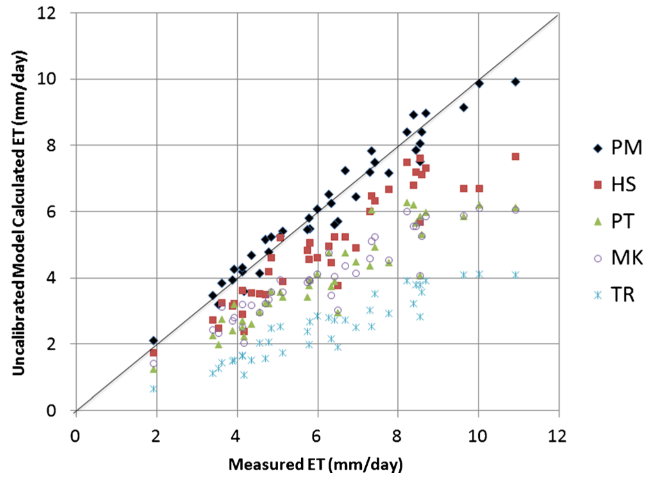

Fig. 6 Measured versus uncalibrated models ET estimates for alfalfa crop in 2010

Results and discussion

Tables 2, 3, and 4 present calibrated ET model evaluation results for the alfalfa, wheat, and potato crops, respectively. For example, evaluation of the calibrated PM model ET estimates versus observed data for the alfalfa crop in 2010 resulted an R^2 value of 0.96, an E value of 0.96, an E_1 value of 0.79, an RMSE of 0.43, and a CRM of −0.004.

The performance ranking of the models for the alfalfa crop was PM > HS > PT > MK > TR, for the wheat crop was PM > PT > HS > MK > TR, and for the potato crop was PM > HS > PT > MK > TR. That is, the FAO-56 PM model remained the top-ranking model for all three crops, while the Makkink and Turc models were consistently ranked fourth and fifth. The main drawback of the Priestley–Taylor model is its high sensitivity to the solar radiation parameter. Data for that parameter may not be locally available (due to dependence on cloud cover). The Hargreaves–Samani model is identified as the

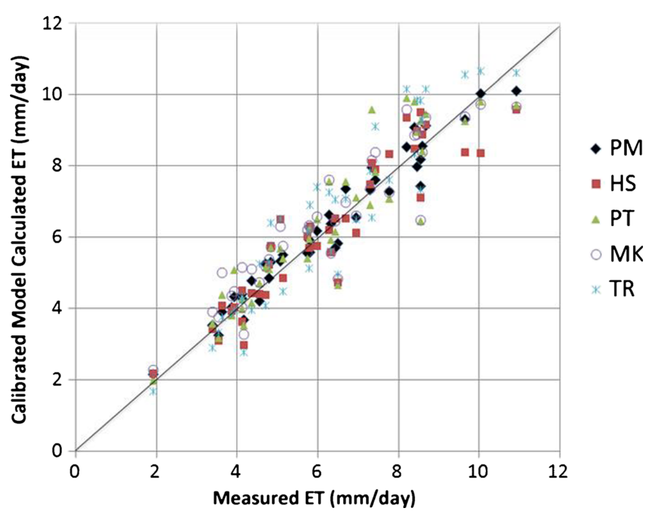

Fig. 7 Measured versus calibrated models ET estimates for alfalfa crop in 2010

Table 1 Statistical analysis of computed crop evapotranspiration models

Coefficient or measure	Equation	Range of values
Coefficient of determination (R^2)	$r^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\overline{O})(P_i-\overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\overline{P})^2}}\right]^2$	0 to 1
Coefficient of efficiency (E)	$E = 1-\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\overline{O})^2}$	$-\infty$ to 1
Modified coefficient of efficiency (E_1)	$E_1 = 1-\frac{\sum_{i=1}^{n}\lvert O_i-P_i\rvert^2}{\sum_{i=1}^{n}\lvert O_i-\overline{O}\rvert^2}$	$-\infty$ to 1
Root mean square error (RMSE)	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{n}}$	0 to ∞
Coefficient of residual mass (CRM)	$CRM = \frac{\sum_{i=1}^{n}O_i-\sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i}$	$-\infty$to∞

O_i and P_i are observed and predicted values, respectively

second best model to FAO-56 PM, with the major advantage the minimal input data requirement of air temperature data.

Penman–Monteith model

The results show that the FAO-56 PM is the most accurate model for estimating crop ET as concluded in several other recent studies (Benli et al. 2006; Al-Omran et al. 2004; DehghaniSanij et al. 2004). Thus, several studies have used FAO-56 PM as the standard equation to calibrate other empirical equations (Allen et al. 2011; ElNesr et al. 2011; Tabari 2010).

Hargreaves–Samani model

As concluded by other studies, the uncalibrated HS model underestimate crop ET in arid environments (Amatya et al. 1995; Jensen et al. 1990; Saeed 1988). Indeed, several authors have been trying to improve the performance of HS by adding rainfall, wind speed, and vapor pressure (Allen et al. 2011; Droogers and Allen 2002). The lack of necessary data in most weather stations, especially in developing countries, significantly limits the application of such models. Therefore, recent studies have adopted a simpler calibration of the HS model. For example, in this study, a correction factor of 1.26 was needed to calibrate the model for the study site. Other recent studies in different climates around the globe have suggested correction factors ranging from 0.74 to 1.82 (Bautista et al. 2009; Ghamarnia et al. 2011; Razzaghi and Sepaskhah 2011; Tabari 2010). However, similar to this study, the HS model ranked directly after the FAO-56 PM when it was tested in semi-arid and arid environments (Benli et al. 2010; Zhao et al. 2014; Nandagiri and Kovoor 2006).

Table 2 Evaluation of the calibrated ET models for alfalfa crop in 2010

N=40	R^2	E	E_1	RMSE	CRM	Rank
PM	0.96	0.96	0.79	0.43	0.004	1
HS	0.87	0.87	0.67	0.75	0.01	2
PT	0.85	0.85	0.66	0.76	0.01	3
MK	0.86	0.86	0.66	0.77	0.01	4
TR	0.88	0.85	0.62	0.81	0.02	5

R^2 coefficient of determination, E coefficient of efficiency, E_1 modified coefficient of efficiency, *RMSE* root mean square error, *CRM* coefficient of residual mass, *PM* FAO-56 Penman–Monteith, *HS* Hargreaves–Samani, *PT* Priestley–Taylor, *MK* Makkink, *TR* Turc

Priestley–Taylor model

The Priestly–Taylor model could not accurately estimate crop ET in the hyper-arid environment of Saudi Arabia unless it was calibrated using a correction factor of 1.58, which is consistent with other studies (Jensen et al. 1990; Mohammad 1997), suggesting the need for a correction factor of 1.39 due to the advection of sensible heat energy. The hyper-arid climate with a moderate to high wind speed during the course of the study led to the PT model varying between the selected crops and ranked from second for wheat to third for the alfalfa and potato crops. The PT ranked right after HS in an arid environment (Nandagiri and Kovoor 2006).

Makkink model

As the statistical analyses above indicate, the Makkink model cannot be used to estimate crop ET with its original uncalibrated parameters. This model underestimated the alfalfa crop ET by about 57 %. Once the model was calibrated, it had far better accuracy than its original equation. However, the MK model ranked fourth compared to the other models for all crops. The MK model is a solar radiation-based model. The average temperature was the second most sensitive parameter in the MK model. The main difference between the PT model

Table 3 Evaluation of the calibrated ET models for wheat crop in 2011

N=10	R^2	E	E_1	RMSE	CRM	Rank
PM	0.95	0.90	0.65	0.29	−0.05	1
PT	0.83	0.82	0.60	0.38	0.01	2
HS	0.67	0.71	0.41	0.49	0.02	3
MK	0.75	0.67	0.38	0.52	−0.03	4
TR	0.68	0.25	0.03	0.79	0.15	5

and the MK model is that the MK model considers solar radiation while the PT model considers net radiation. The MK model has an advantage over the PT model because net radiation is difficult to measure (Allen et al. 1998).

Turc model

The previous discussions show that the empirical models used in this study are reliable when applied in areas for which they were developed. However, large errors can be expected once they are extrapolated to climatic areas without calibrating the model using local data. As the analyses show, the Turc model had the worst performance of all five models for estimating crop ET both before and after calibration. Similar to this study, Mohammad (1997) reported that the Turc model underestimated crop ET. Accordingly, the TR model was calibrated with a large correction factor of 2.62 to fit the conditions of the Wadi Al-Dawasir region. However, seasonal change remained a major source of error for this model, indicating that the model must be calibrated on a seasonal basis to provide a better performance. This model is not recommended for use in the Wadi Al-Dawasir region.

Conclusion

This study concludes that FAO-56 PM is the most accurate ET model for estimating crop water irrigation needs in hyper-arid environments. This model is highly sensitivity to air temperature and wind speed, has medium sensitivity to solar radiation and low sensitivity to relative humidity. However, the major drawback of this model is that local wind speed, solar radiation, and relative humidity information may not be available.

Table 4 Evaluation of the calibrated ET models for potato crop in 2011

ET_m	R^2	E	E_1	RMSE	CRM	Rank
PM	0.97	0.95	0.78	0.33	0.02	1
HS	0.77	0.82	0.62	0.63	0.04	2
PT	0.83	0.80	0.55	0.66	0.04	3
MK	0.64	0.76	0.55	0.73	−0.02	4
TR	0.86	0.73	0.47	0.77	0.13	5

Both Turc and Makkink solar radiation-based ET models provided the least accurate estimates even after calibration, while the calibrated Hargreaves–Samani temperature-based model provided the second best after FAO-56 PM ET estimates for irrigation scheduling in hyper-arid environments. The main advantage of the Hargreaves–Samani model over the FAO-56 PM model is that it does not require wind speed or relative humidity data. The most sensitive parameter for this model is air temperature, which is readily available at most sites and is one of the key parameters included in the hourly weather forecasts.

All ET models (except for FAO-56 PM) needed calibration with local site data. These ET models, if used with default original published parameters (i.e., without calibration), would result in significant underestimation of irrigation water needs. For example, the Hargreaves–Samani model would underestimate by 20 %; the Priestley–Taylor and Makkink models would underestimate by 35 %; and the Turc model would underestimate by 60 %. The Turc model is highly sensitive to relative humidity, which is an insignificant parameter in hyper-arid environments. In fact, using these models (without calibration) for irrigation water demand will put the crop under water stress and a production loss would be expected.

The performance of the empirical models improved, once they were calibrated to the measured alfalfa crop ET. The surprisingly good performance of the simple Hargreaves–Samani equation, which only requires air temperature data with the new calibrated coefficient 0.0029, provides an opportunity for improved water conservation through more accurate irrigation scheduling. The performance of other radiation-based models varied. MK and PT are ranked third and fourth with a slight difference between them. The new calibrated coefficients obtained for MK and PT models were 1.99 and 0.963, respectively.

The main drawback of the FAO-56 PM model is that it requires extensive lists of meteorological data that are often not locally available, particularly in developing countries such as Saudi Arabia. Most irrigated regions in Wadi Al-Dawasir have limited access to local climatic data, and weather forecasts are limited to the air temperature. Therefore, the need for a simple model such the calibrated Hargreaves–Samani model is a very beneficial tool for improving water conservation through more efficient irrigation scheduling.

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References

Abderrahman W A (2001) Water demand management in Saudi Arabia. http://web.idrc.ca/en/ev-93954-201-1-DO_TOPIC.html. Accessed 15 Mar 2012

Alazba AA, Alghobari HM, Mohammad FS, Alomran AM (2003) Measured and estimated crop ET and Kc for wheat and barley in central Saudi Arabia. Alex J Agric Res 48(2):1–9

Al-Ghobari HM (2000) Estimation of reference evapotranspiration for southern region of SaudiArabia. Irrig Sci 19(2):81–86

Allen RG (2008) Quality assessment of weather data and micrometeological flux—impacts on evapotranspiration calculations. J Agric Meteorol 64(4):191–204

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. Irrig Drain paper No. 56, FAO, Rome, 300 p

Allen RG, Pereira LS, Howell TA, Jensen ME (2011) Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agric Water Manag 98(6):899–920

Al-Mogrin S (2001) Treatment and reuse of wastewater in Saudi Arabia. In: Proceedings, Expert Consultation for Launching the Regional Network on Wastewater in the Near East

Al-Omran AM, Mohammad FS, Al-Ghobari HM, Alazba AA (2004) Determination of evapotranspiration of tomato and squash using lysimeter in central Saudi Arabia. Int Agric Eng J 13(1&2):27–36

Amatya DM, Skaggs RW, Gregory JD (1995) Comparison of methods for estimating REF-ET. J Irrig Drain Eng 121(6):427–435

Bautista F, Bautista D, Delgdao-Carranza C (2009) Calibration of the equation of Hargreaves and Thornthwaite to estimate the potential evapotranspiration in semi-arid and subhumid tropical climates for regional applications. J Atomsfera 22(4):331–348

Benli B, Kodal S, Ilbeyi A, Ustun H (2006) Determination of evapotranspiration and basal crop coefficient of alfalfa with a weighing lysimeter. Agric Water Manag 81(3):358–370

Benli B, Bruggeman A, Oweis T, Ustun H (2010) Performance of Penman-Monteith FAO56 in a semiarid highland environment. J Irrig Drain Eng 136(11):757–765

DehghaniSanij H, Yamamoto T, Rasiah V (2004) Assessment of evapotranspiration estimation models for use in semi-arid environments. Agric Water Manag 64(2):91–106

Dinpashoh Y, Jhajharia D, Fakheri-Fard A, Singh VP, Kahya E (2011) Trends in reference crop evapotranspiration over Iran. J Hydrol 399(3–4):422–433. doi:10.1016/j.jhydrol.2011.01.021

Droogers P, Allen RG (2002) Estimating reference evapotranspiration under inaccurate data conditions. Irrig Drain Syst 16(1):33–45

ElNesr M, Alazba A (2010) Simple statistical equivalents of Penman–Monteith formula's parameters in the absence of non-basic climatic factors. Arabian J Geosci 1–11

ElNesr MN, Alazba AA, Amin MT (2011) Modified Hargreaves' method as an alternative to the Penman-Monteith method in the kingdom of Saudi Arabia. Aust J Basic Appl Sci 5(6):1058–1069

FAO (2008) Irrigation in the Middle East region in figures: AQUASTAT Survey - 2008. ftp://ftp.fao.org/agl/aglw/docs/wr34_eng.pdf. Accessed 15 Oct 2011

Farahani HJ, Howell TA, Shuttleworth WJ, Bausch WC (2007) Evapotranspiration: progress in measurement and modeling in agriculture. Trans of the ASAE 50(5):1627–1638

Ghamarnia H, Rezvani V, Khodaei E, Mirzaei H (2011) Time and place calibration of the Hargreaves equation for estimating monthly reference evapotranspiration under different climatic conditions. J Agric Sci 4(3):111–122

Hargreaves GH, Allen RG (2003) History and evaluation of Hargreaves evapotranspiration equation. J Irrig Drain Eng 129(1):53–63

Hargreaves GH, Samani ZA (1985) Reference crop evapotranspiration from temperature. Appl Eng Agric 1(2):96–99

Ismail SM (1993) Reference evapotranspiration study in Al-Qassim region. J Agric Sci 5(2):141–151

Jensen ME, Haise HR (1963) Estimating evapotranspiration from solar radiation. J Irrig Drain Div ASCE 89:15–41

Jensen M E, Burman R D, Allen R G (1990) "American Society of Civil Engineers". Committee on Irrigation Water Requirements. Evapotranspiration and irrigation water requirements: a manual. New York

Makkink GF (1957) Testing the Penman formula by means of lysimeters. J Inst Water Eng 11(3):277–288

Mohammad FS (1997) Calibration of reference evapotranspiration equations for alfalfa under arid climatic conditions. J King Saud Univ Agric Sci 9(1):39–56

Nandagiri L, Kovoor GM (2006) Performance evaluation of reference evapotranspiration equations across a range of Indian climates. J Irrig Drain Eng 132(3):238–249

Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc R Soc London Series A NATO ASI Ser 193(1032):120–145

Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large-scale parameters. Mon Weather Rev 100(2):81–92

Razzaghi F, Sepaskhah AR (2011) Calibration and validation of four common ET0 estimation equations by lysimeter data in a semi-arid environment. Arch Agron Soil Sci 58(3):303–319

Saeed M (1988) Simple equations for estimating reference evapotranspiration in an arid climate, Saudi Arabia. Arab Gulf J Sci Res 6(3): 325–338

Tabari H (2010) Evaluation of reference crop evapotranspiration equations in various climates. Water Resour Manag 24(10):2311–2337

Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38(1):55–94. doi:10.2307/210739

Todorovic M, Karic B, Pereira LS (2013) Reference evapotranspiration estimate with limited weather data across a range of mediterranean climates. J Hydrol 481:166–176. doi:10.1016/j.jhydrol.2012.12.034

Turc L (1961) Evaluation de besoins en eau d'irrigation, ET potentielle. Ann Agron 12:13–49

Zhang Y, Yu Q, Liu C, Jiang J, Zhang X (2004) Estimation of winter wheat evapotranspiration under water stress with two semiempirical approaches. Agron J 96(1):159–168

Zhao S, Yang Y, Zhang F, Sui X, Yao Y, Zhao N, Zhao Q, Li C (2014) Rapid evaluation of reference evapotranspiration in Northern China. Arabian J Geosci. doi:10.1007/s12517-013-1263-0