Evaluation of evapotranspiration models for estimating daily reference evapotranspiration in arid and semiarid environments

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ABSTRACT

Daily outputs from eight evapotranspiration models were tested against reference evapotranspiration (ET_o) data computed by FAO56PM to assess the accuracy of each model in estimating ET_o. Models were compared at eight stations across Jordan. Results show that Hargreaves modified models were the best in light of mean biased error (MBE), root mean square error (RMSE) and mean absolute error (MAE). The MBE, RMSE, and MAE values ranged from –1.47 to 0.81, 3.87 to 1.14 and 0.87 to 3.15 mm/day for HarM1, and from –1.45 to 0.89, 1.08 to 3.91, and 0.85 to 3.16 mm/day for HarM2, respectively, which would make it the best models in light of the MBE, RMSE and MAE ranging from –6.18 to 2.79, 6.90 to 1.08 and 4.74 to 0.85 mm/day for all models and stations. Comparisons were also made using three composite regions: countrywide, semiarid, and arid regions. In conclusion, local calibration is needed for the whole models or the linear regression can be used to calculate the ET_o.

Keywords: modelling; FAO56 Penman-Monteith; evapotranspiration; Jordan

The United Nations of Food and Agricultural Organization (FAO) proposed a methodology for computing crop evapotranspiration (ET_o) and crop coefficient (K_c) (Doorenbos and Pruitt 1977). These coefficients depend on several factors including crop type, stage of crop growth, canopy height and density (Allen et al. 1998). To schedule irrigation properly, an accurate and standard method to estimate ET_o to predict crop water requirements, was stated by several authors (Chiew et al. 1995; Allen 1996). A great number of models was developed to estimate ET_o for use in environments that lack direct ET_o measurements (Pereira and Pruitt 2004, Gavilán et al. 2006). A major complication in ET_o estimation using these models is the requirement for meteorological data that may not be easily available. This restriction at times prohibits use of more accurate models, and necessitates the use of models that have less demanding data requirements.

An international scientific community has accepted the FAO56 Penman-Monteith (FAO56PM) model as the most precise one for its good results when compared with other models in various regions of the entire world (Chiew et al. 1995, Garcia et al. 2004, Gavilán et al. 2006). Estimation of reference ET_o by globally accepted FAO56PM (Allen et al. 1998) requires the weather parameters like maximum and minimum temperature, solar radiation, sunshine hours, wind speed, relative humidity. However, for many locations, as is the case for Jordan, such meteorological variables are often incomplete and/or not available. Furthermore, no published studies have examined the applicability of ET_o models across Jordan, a country with a great gradient in temperature and precipitation. Moreover, the local calibration and validation of other models is more important in semiarid and arid regions than the temperate climate because most of these models were calibrated and validated in temperate environment (Dehghani Sanji et al. 2003). The objectives of this study were to (1) assess the performance of simpler models that require less readily available data against FAO56PM, and (2) to determine models performance across spaces in Jordan, focusing on arid versus semiarid environment.

Table 1. Weather stations used in this study

Station	North latitude	East longitude	Altitude (m)	Rain (mm)	Climate
Sammer	31°58'58''	31°58'52''	616	565	semiarid
Amman airport	31°58'17''	35°59'19''	766	300	semiarid
Ghor Al-Safi	31°31'58''	35°27'59''	–350	80	arid
Al-Rabh	31°15'57''	35°45'07''	920	336	semiarid
Umjmal	32°19'36''	36°22'20''	672	163	arid
Riweished	32°30'27''	38°12'30''	865	75	arid
Al-Shunah Al-jnoubiyh	31°15'54''	35°30'58''	–300	115	arid
Aqaba	29°32'2''	35°6'5''	51	50	arid

MATERIALS AND METHODS

Climatic data. All selected weather stations (Table 1) have good quality daily data records from 2002 to 2006 for estimating ET_o with FAO56PM model including solar radiation, sunshine duration, relative humidity, wind speed and daily maximum and minimum temperatures. Since the whole selected stations are located in non-reference weather sites, daily temperatures were corrected with the proposed method by Allen et al. (1998). The qualities of the climatic records were checked (Allen et al. 1998).

Evapotranspiration estimation models. Eight evapotranspiration models: Penman model (PE) (Penman 1948), Makkink (Makk) (Makkink 1957), Priestly-Taylor (PT) (Priestley and Taylor 1972), FAO24Pan Evaporation (FAO24P) (Allen et al. 1998), FAO24 Radiation (FAO24RD) (Jensen et al. 1997), Hargreaves original (Har), Hargreaves Modified 1 (HarM1), and Hargreaves Modified 2 (HarM2) (Allen et al. 1998) were used to estimate ET_o. The model selection was based on the complexity or simplicity of the models, and the quality and quantity of the weather data (Table 2). These eight models were used to compute ET_o using daily weather data (Table 2). The eight models have advantages and disadvantages in terms of input data requirements and quality of results. A primary goal of this study was to identify the model that most closely approximates FAO56PM while considering the input data required.

The FAO56PM model is given by:

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma(900/(T_{mean} + 373))\,u_2\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)}$$

Where: T_{mean} is average daily air temperature (°C), 900 is a conversion factor, ET_o is the standardized reference crop ET (mm/day); R_n is net radiation at the crop surface (MJ/m^2/day); G is soil heat flux at the soil surface (MJ/m^2/day); u_2 is mean daily (m/s); e_s is mean saturation vapor-pressure (kPa); e_a is mean actual vapor-pressure (kPa); Δ is slope of the saturation vapor-pressure-temperature curve (kPa/C); γ is psychrometric constant (kPa/C), e_a was calculated based on temperature and relative humidity, and net radiation was calculated from the difference between the incoming

Table 2. Climate parameters required by the reference evapotranspiration models

	FAO56PM[a]	PE[b]	Har[c]	HarM1[d]	HarM2[d]	F24R[f]	PT[i]	Makk[j]	FAO24P[k]
Maximum temperature (°C)	×	×	×	×	×	×	×	×	
Minimum temperature (°C)	×	×	×	×	×	×	×	×	
Humidity (%)	×	×				×			×
Wind speed (m/s)	×	×				×			×
Solar radiation (MJ/m^2/day)	×	×				×	×	×	
Evaporation (mm)									×

[a]FAO56 penman-Monteith; [b]Penman method; [c]Hargreaves model (original); [d]Hargreaves modified model1; [e]Hargreaves modified model2; [f]FAO24 Radiation model; [i]Priestley-Taylor model, [j]Makkink; [k]FAO24Pan method

net shortwave radiation and outgoing net longwave radiation (Allen et al. 1998).

The original form of the Penman model (Penman 1948) used for estimation of daily ET_o (mm/day) is:

$$ET_o = \frac{(\Delta/(\Delta + \gamma))(R_n - G) + K_w(\gamma(\Delta + \gamma))(a_w + b_w u_2)(e_s - e_a)}{\lambda}$$

Where: K_w is a unit constant (6.43), a_w and b_w the wind function coefficients, u_2 the wind speed (m/s), λ the latent heat of vaporization (MJ/kg). The a_w and b_w are empirical constants and were usually computed for regional requirement. In general, the values for a_w and b_w are 1.0 and 0.536, respectively, and we used these values in our ET_o computation. Other notations have the same meaning and units as in FAO56PM Equation.

The original type of Hargreaves model (Har) (Allen et al. 1998) is as follows:

$$ET_o = 0.408 \times 0.0023 \times (T_{mean} + 17.8) \times (T_{mean} - T_{min})^{0.5} \times R_a$$

Droogers and Allen (2002) reported two new types of Hargreaves models (HarM1 and HarM2, respectively) as follows:

$$ET_o = 0.408 \times 0.0030 \times (T_{mean} + 20) \times (T_{mean} - T_{min})^{0.4} \times R_a$$

$$ET_o = 0.408 \times 0.0025 \times (T_{mean} + 16.8) \times (T_{mean} - T_{min})^{0.5} \times R_a$$

Where: ET_o is the reference evapotranspiration (mm/day), T_{mean} is the mean air temperature (°C), T_{max} is the daily maximum temperature (°C), T_{min} is the daily minimum temperature (°C), and R_a is the daily extraterrestrial radiation (mm/day).

The FAO24RD method was first introduced by Doorenbos and Pruitt (1977) as a modification of the Makkink (1957) method (Doorenbos and Pruitt 1977, Jensen et al. 1990). The form of FAO24RD given by Jensen et al. (1990) is described as:

$$ETo = a + b\left[\frac{\Delta}{\Delta + \gamma} Rs\right]$$

Where: a = –0.3 mm/day, and b calculated using a regression equation function of RH_{mean} and average day time wind speed (Jensen et al. 1997).

Priestley and Taylor (1972) proposed a simplified version of the combination equation (Penman 1948) for use when surface areas were generally wet, which is a condition required for potential ET_o. The aerodynamic component was deleted and the energy component was multiplied by a coefficient, $\alpha = 1.26$, where $\alpha = 1.26$ is an empirically determined dimensionless correction, which is given by:

$$ETo = \alpha \frac{\Delta}{\Delta + \gamma}(Rn - G)$$

Where: ET_o is in mm/day, other notations have the same meaning and units as in FAO56PM Equation.

For estimating potential evapotranspiration (mm/day) from grass, Makkink (1957) proposed the following equation:

$$ETo = 0.61\left(\frac{\Delta}{(\Delta + \gamma)}\right)\left(\frac{Rs}{\lambda} - 0.12\right)$$

Where: R_s is the total solar radiation in MJ/m^2/day; other notations have the same meaning and units as in FAO56PM Equation.

Doorenbos and Pruitt (1977) described a method to convert pan evaporation to ET_o. This method adjusts the measured pan evaporation by a coefficient to estimate ET_o. The basic form of the FAO24P model, as described by Allen et al. (1998) is:

$$ET_o = K_p E_{pan}$$

$$K_p = 0.108 - 0.028U_2 + 0.0422 \ln(FET) + 0.1434 \ln(RH_{mean}) - 0.000631 [\ln(FET)]^2 \ln(RH_{mean})$$

Where: ET_o is in mm/day, K_p is the pan coefficient, E_{pan} is the pan evaporation (mm/day), U_2 is the average daily wind speed at 2 m (m/s), FET is the fetch distance of the green crop (m), and RH_{mean} is mean daily relative humidity (%). The limits are: U_2 must be between 1–8 m/s, RH_{mean} must be between 30 and 84%, and the fetch distance must be between 1–1000 m (Allen et al. 1998). Due to the variable nature of the environment around the evaporation pans used in this study, a fetch distance of 1000 m was assumed as suggested by Allen (2003). Standard weather bureau Class A evaporation pan (122 cm diameter by 25 cm height) at the weather stations was manually (hook gage) measured. The water level in the pan usually maintained within 7.5–12.5 cm of the lip. The pan is noninsulated and rests on a wooden platform 13 cm above the ground. Irrigated and non-irrigated grass grows to the edge of the wooden frame. Daily E_p measurements were made at about 8:00 a.m.

Statistical analysis. The ET_o estimation obtained using a given model was tested using the statistical parameters: intercept, slope, regression coefficient, root mean square error (RMSE), mean bias error (MBE) and mean absolute error (MAE). The following equations were used for the computation of the aforementioned parameters:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\overline{X} - X_{FAO\ 56\ PM})}{n}}$$

$$MBE = \frac{\sum_{i=1}^{n}(\overline{X} - X_{FAO\ 56\ PM})}{n}$$

$$MAE = \frac{\sum_{i=1}^{n}\left|(\overline{X} - X_{FAO\ 56\ PM}\right|}{n}$$

Table 3. Countrywide, arid and semiarid comparison and regression analysis between ET_o estimation models and FAO56PM

Models	MBE (mm/day)	RMSE (mm/day)	MAE (mm/day)	r^2	Slope[a]	Intercept[b]
Countrywide						
PE	–4.78	5.48	4.79	0.83	1.59	2.40
Har	–2.75	4.19	3.10	0.41	0.93	3.05
HarM1	–0.05	2.12	1.53	0.45	0.46	2.25
HarM2	0.00	2.14	1.52	0.44	0.48	2.11
FAO24R	–2.74	3.53	2.96	0.60	0.95	2.96
PT	–2.56	3.80	2.96	0.44	0.87	3.10
Makk	2.25	3.23	2.29	0.48	0.23	0.87
FAO24P	–2.79	4.61	3.45	0.25	0.71	3.94
Semiarid area						
PE	–4.10	4.21	4.12	0.91	1.80	1.24
Har	–2.19	3.21	2.42	0.60	1.20	1.46
HarM1	–0.11	1.41	1.06	0.64	0.61	1.48
HarM2	–0.01	1.39	1.03	0.64	0.64	1.31
FAO24R	–2.91	3.50	3.01	0.68	1.19	2.23
PT	–2.78	3.75	2.99	0.53	1.14	2.29
Makk	1.82	2.52	1.89	0.57	0.31	0.65
FAO24P	–2.60	3.84	3.03	0.39	0.96	2.72
Arid area						
PE	–5.34	6.04	5.34	0.79	1.47	3.24
Har	–3.19	4.83	3.64	0.32	0.77	4.23
HarM1	0.02	2.56	1.90	0.35	0.38	2.77
HarM2	0.03	2.58	1.90	0.35	0.34	2.67
FAO24R	–2.60	3.26	2.92	0.57	0.85	3.28
PT	–2.38	3.84	2.93	0.41	0.76	3.45
Makk	2.63	3.72	2.64	0.45	0.20	0.96
FAO24P	–2.93	5.15	3.81	0.17	0.57	4.85

[a, b]slope and intercept of the regression equation

RESULTS AND DISCUSSION

The statistical analysis components associated with the different models for estimating ET_o are given in Tables 3–5. Instead of giving figures for all eight methods, the statistical parameters are given in Tables 3–5. Ideally the intercept should be close to 0, however, for countrywide, semiarid and arid climate the intercepts were always higher than 0.87, 0.65 and 0.96 mm/day, respectively. While the intercept were higher than 0.48 for the regression analysis between the estimated ET_o of each model and FAO56PM at each station (Tables 4 and 5). Similarly, the slope should be close to 1, however, in all the cases the slope showed a wide variation among the models. The slope range from 0.14 for Makk model at Ghor Al-Safi and Aqaba stations to 1.93 for PE model at Al-Rubh station (Tables 3–5). However, such statistical testing of intercept and slope is much more rigorous, and so other methods are used to evaluate models performance.

A correlation coefficient (r^2) is used to reflect how the estimated ET_o best matches with the FAO56PM estimation, RMSE and MBE also represent the deviation of estimated ET_o from the FAO56PM estimation, and it does so in a more comprehensive manner (Kobayashi and Salam 2000). Even though, the linear regression can make the simplified models produce similar estimations to FAO56PM, which would be meaningful in real applications. The inference drawn on the basis of just r^2 can be erroneous in identification of the model performance. For example, the positive cor-

Table 4. Comparison and regression analysis between ET_o estimation models and FAO56PM estimation at Sammer, Amman airport, Ghor Al-Safi, Al-Rubh and Umm-Jmal

Models	MBE (mm/day)	RMSE (mm/day)	MAE (mm/day)	r^2	Slope[a]	Intercept[b]
Sammer						
PE	–4.36	4.99	4.37	0.92	1.91	0.94
Har	–2.66	3.88	2.93	0.60	1.40	1.16
HarM1	–0.16	1.39	1.03	0.65	0.68	1.39
HarM2	–0.09	1.39	1.01	0.65	0.71	1.19
FAO24R	–2.86	3.56	3.07	0.66	1.23	1.99
PT	–3.05	4. 08	3.36	0.55	1.26	2.06
Makk	1.96	2.59	2.02	0.57	0.33	0.59
FAO24P	–2.84	3.88	3.12	0.41	0.94	3.08
Amman airport						
PE	–4.14	4.69	4.15	0.88	1.66	1.54
Har	–1.97	3.10	2.23	0.52	1.02	1.90
HarM1	0.23	1.67	1.23	0.54	0.53	1.62
HarM2	0.32	1.68	1.23	0.54	0.55	1.45
FAO24R	–2.36	2.93	2.42	0.70	1.08	2.05
PT	–2.02	3.29	2.31	0.44	0.94	2.25
Makk	2.32	3.00	2.34	0.53	0.26	0.61
FAO24P	–0.50	2.31	1.62	0.43	0.77	1.42
Ghor Al-Safi						
PE	–3.77	4.02	3.77	0.96	1.51	1.31
Har	–3.65	4.43	3.72	0.66	1.39	1.78
HarM1	–0.19	1.25	0.87	0.72	0.68	1.71
HarM2	–0.18	1.25	0.85	0.72	0.72	1.52
FAO24R	0.27	1.42	0.93	0.68	0.52	2.06
PT	–0.15	1.33	0.95	0.68	0.63	1.94
Makk	3.58	4.10	3.59	0.66	0.14	0.54
FAO24P	–4.26	4.73	4.31	0.49	0.87	4.89
Al-Rubh						
PE	–3.79	4.41	3.81	0.93	1.93	1.03
Har	–1.94	2.49	2.08	0.72	1.17	1.44
HarM1	–0.38	1.14	0.93	0.76	0.64	1.45
HarM2	–0.23	1.08	0.86	0.77	0.66	1.25
FAO24R	–3.48	3.93	3.49	0.78	1.42	2.22
PT	–3.22	3.85	3.26	0.68	1.36	2.16
Makk	1.25	1.90	1.37	0.37	0.62	0.71
FAO24P	–4.33	4.70	4.08	0.69	1.53	2.44
Umm-Jmal						
PE	–4.73	5.42	4.74	0.90	1.62	1.82
Har	–1.52	2.94	2.14	0.53	0.79	2.51
HarM1	0.81	2.34	1.59	0.58	0.43	1.88
HarM2	0.89	2.36	1.60	0.58	0.44	1.74
FAO24R	–2.73	3.46	2.86	0.73	1.08	2.36
PT	–2.16	3.71	2.56	0.47	0.87	2.77
Makk	2.79	3.77	2.81	0.56	0.25	0.75
FAO24P	0.01	2.47	1.81	0.48	0.62	1.82

[a, b]slope and intercept of the regression equation

Table 5. Comparison and regression analysis between ET_o estimation models and FAO56PM estimation at Riweished, Al-Shunh Al-janoubiyh and Aqaba

Models	MBE (mm/day)	RMSE (mm/day)	MAE (mm/day)	r^2	Slope	Intercept
Riweished						
PE	–5.03	5.76	5.03	0.90	1.74	1.29
Har	–3.53	4.68	3.67	0.64	1.31	1.98
HarM1	0.53	1.83	1.36	0.66	0.60	1.51
HarM2	0.48	1.80	1.35	0.66	0.64	1.37
FAO24R	–2.39	3.30	2.76	0.70	1.14	1.66
PT	–2.01	3.60	2.69	0.55	1.10	1.51
Makk	3.10	3.81	3.10	0.59	0.29	0.48
FAO24P	–0.18	2.34	1.74	0.50	0.59	1.37
Al-Shunh Al-janoubiyh						
PE	–6.18	6.90	6.18	0.59	1.66	4.05
Har	–4.58	5.73	4.64	0.33	1.18	3.98
HarM1	–1.47	2.35	2.02	0.35	0.59	2.80
HarM2	–1.45	2.38	2.01	0.35	0.63	2.66
FAO24R	–3.47	4.38	3.49	0.37	0.89	4.43
PT	–4.01	4.79	4.06	0.40	1.06	3.82
Makk	1.32	2.12	1.32	0.36	0.24	1.13
FAO24P	–4.86	5.86	4.91	0.37	1.22	4.13
Aqaba						
PE	–5.77	6.29	5.77	0.85	1.27	4.38
Har	–3.02	5.76	4.24	0.31	0.33	4.44
HarM1	0.33	3.87	3.15	0.36	0.19	4.82
HarM2	0.33	3.91	3.16	0.36	0.20	4.79
FAO24R	–1.66	2.79	2.39	0.73	0.62	3.66
PT	–1.43	3.14	2.66	0.56	0.54	3.79
Makk	3.37	4.97	3.39	0.61	0.14	1.05
FAO24P	–4.36	5.93	4.70	0.31	0.32	5.89

relation between the HarM1 and HarM2 estimation and FAO56PM estimation is relatively poor for arid climate area (0.32 and 0.35, respectively). The MBE, RMSE, and MAE values ranged from –1.47 to 0.81, 3.87 to 1.14 and 0.87 to 3.15 mm/day for HarM1, and from –1.45 to 0.89, 1.08 to 3.91, and 0.85 to 3.16 mm/day for HarM2, respectively, which would make it the best model based on MBE, RMSE and MAE which ranged from –6.18 to 2.79, 6.90 to 1.08 and 4.74 to 0.85 mm/day for all models and station, respectively (Tables 3–5). Conversely, PE had the highest correlation (0.59–0.93) among all ET_o models. However, its MBE , RMSE and MAE values ranged from –6.18 to –3.77, 4.02 to 6.90 and 3.77 to 6.18 mm/day, which is on the higher side of MBE, RMSE and MAE, indicating a poorer performance by the model. These results showed that even though the estimated ET_o and ET_oFAO56PM had a good linear relationship, the prediction is greatly biased, as indicated by a high MBE, RMSE and MAE values.

The countrywide performance are shown in Table 3, in terms of MBE, RMSE and MAE values, the HarM1 and HarM2 models showed the lowest MBE, RMSE and MAE values at –0.05, 2.12 and 1.53 and 0.00, 2.14 and 1.52 mm/day, and values of r^2 were 0.44 and 0.45 for HarM1 and HarM2, respectively. The least effective model for countrywide is the PE model with MBE, RMSE and MAE values at –4.78, 5.48 and 7.79 mm/day, respectively, although r^2 (0.83) was the highest among the tested models.

The semiarid and arid regions were slightly different. HarM1 and HarM2 showed higher r^2 for semiarid region (0.60–0.64) compared with arid region. However, both models still showed the lowest MBE, RMSE and MAE among other models. Results at individual stations varied spatially. In general, HarM1 and HarM2 were the best models with HarM1 and HarM2 leading the whole stations. The least accurate model for each station was more difficult to ascertain than that the best model. The PE, Har and FAO24P tended to generate the highest MBE, RMSE, and MAE at most stations. The PT, FAO24R, and Makk models tended to perform moderately to poorly, often relatively high values of MBE, RMSE and MAE and/or low r^2 (Tables 4 and 5). The MBE values indicate that the overall ET_o estimated by the models were under predicted compared with ET_o FAO56PM. The reason can be explained because of its semiarid and arid climate. The Hargreaves equations tend to overestimate ET_o in humid regions and to underestimate it in dry regions (Saeed 1986, Amatya et al. 1995, Allen et al. 1998, Temesgen et al. 1999, Samani 2000, Droogers and Allen 2002, Xu and Singh 2002, Fooladmand and Haghighat 2007). It has also been shown that Hargreaves equations tend to overestimate ET_o at low ET_o rates and to underestimate it at high ET_o rates (Droogers and Allen 2002, Xu and Singh 2002). Therefore, the Hargreaves equations as well as other models require local calibration before applying it for daily ET_o estimation at a given region (Jensen et al. 1997, Xu and Singh 2002). Moreover, the results shown in this paper suggest that a qualitative calibration of the models should be performed at semiarid and arid regions.

However, ET_o is only the half story when discussing the irrigation scheduling. ET_o basis irrigation can be applied when no major soil water limit and also, when plant tissues are sufficiently hydrated, which must not always be the case (Cohen et al. 2005). Besides, irrigation to maintain non-limiting soil water conditions is not always the best option for water and nutrient management. In a study done by Nadezhdina (1999), he found that under conditions (non-limiting soil water) of high evaporative demand, sap flow reached a maximum early in the day and remained at that value for most of the day, whereas leaf water potential decreased below the critical limit value. This mean that even when sap flow was high, water was not used efficiently under conditions of high evaporative demand, although it is use contributed to plant survival (Nadezhdina 1999). Another limitation of ET_o approach also is that full irrigation may not required to maximize fruit yield or quality. For example, Moriana et al. (2003) showed that a decrease in olive productivity was observed when irrigation application approached that of maximum crop water requirement (ET_c). Thus, ET_o models can help to choose an appropriate deficit irrigation approach by combining ET_o information with the crop performance and soil water content (Fernandez et al. 2001, 2008). Therefore, irrigation can be carried out according to recommendations based on ET_o and crop coefficients, with adjustments according to crop water status assessments such as leaf water potential measurements, plant stem diameter, and sap flow measurements.

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