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Evaluation of Class A Pan Coefficient Models for Estimation of Reference Crop Evapotranspiration in Cold Semi-Arid and Warm Arid Climates

Ali-Akbar Sabziparvar · H. Tabari · A. Aeini · M. Ghafouri

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Abstract Evapotranspiration and evaporation measurements are important parameters for many agricultural activities such as water resource management and environmental studies. There are several models which can determine pan coefficient (K_{Pan}), using wind speed, relative humidity and fetch length conditions. This paper analyses seven exiting pan models to estimate K_{Pan} values for two different climates of Iran. Monthly mean reference crop evapotranspiration (ET_0) was calculated according to the pan-ET_0 model. The results showed that estimated pan coefficients by majority of the suggested models were not statistically accurate to be used in the pan-ET_0 conversion method. However, for the cold semi-arid climate condition, the best K_{Pan} models for estimation of ET_0 were Orang and Raghuwanshi–Wallender, respectively. Also, the Snyder and Orang models were best fitted models for warm arid climate, respectively. The mean annual value of K_{Pan}, determined by Penman–Monteith FAO 56 (PMF-56) standard model for warm arid sites, was approximately 32% higher than the corresponding value in the cold semi-arid climate. Similarly, the mean annual ET_0 in the warm arid sites was 66% higher, compared to the ET_0 of the cold semi-arid sites. These types of warm arid and semi-arid climates are found widely throughout the world.

A.-A. Sabziparvar (✉)
Meteorology, College of Agriculture, Bu-Ali Sina University, Hamedan, 65178, Iran
e-mail: swsabzi@basu.ac.ir

H. Tabari · A. Aeini
College of Agriculture, Bu-Ali Sina University, Hamedan, 65174, Iran

M. Ghafouri
Hydrology, Soil & Water Conservation and Watershed Management Research Center,
Tehran, PO Box 13445-1136, Iran

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1 Introduction

According to the UNEP (1992) definition of the three arid zones (hyper-arid, arid and semiarid), we are dealing with about 48.53 million km^2, or 37.30% of the Earth land surface, a massive biome extending over huge areas of Africa and Asia, as well as considerable areas of Australia, North and South America. Apart from 18 countries entirely suited in arid world, such as Mauritania, Egypt and Saudi Arabia, there are 49 countries with at least part of their territories within the arid world, such as Morocco, Mali, Chad, Iran, India, Australia, Chile and South Africa. These countries are important for agricultural production. They are largely dependent upon external sources for their renewable water supplies. The growth of large cities within a million inhabitants or more exacerbates population concentrations in the arid word even more. Considering the recent increasing populations of many of countries in these areas, and the low density of reliable meteorological networks, accurate estimation of K_{Pan} to provide reliable estimates of ET_0 is needed for optimising water use efficiency in these areas. By considering trends in climate, and trends in the most useful models to estimate K_{Pan} (compared against observations of K_{Pan}), our findings are relevant to irrigation managers in these climates acknowledging current changes in climate.

Evaporation and evapotranspiration processes are the major components of the hydrologic cycle which play a vital role in agricultural and hydro-meteorological studies as well as in the operation of reservoirs, design of irrigation and drainage systems, water resources management and irrigation scheduling (Ozturk and Apaydin 1998; Lee et al. 2004; Snyder et al. 2005; Lopez-Urrea et al. 2006; Gundekar et al. 2008). The crop evapotranspiration ($\mathrm{ET_C}$) is estimated by reference crop evapotranspiration (ET_0) multiplied by the crop coefficient (K_{C}). One common method to estimate ET_0 is converting the class A pan evaporation (E_{Pan}) into ET_0 by using a pan coefficient (K_{Pan}) (Sentelhas and Folegatti 2003; Yeh 2006; Martínez Alvarez et al. 2007). In pan method, the following relationship is used:

$$ET_0 = K_{\mathrm{Pan}} \cdot E_{\mathrm{Pan}} \tag{1}$$

where ET_0 is the reference crop evapotranspiration (mm day^{-1}), E_{Pan} the measured class A pan evaporation (mm day^{-1}) and K_{Pan} the pan coefficient (Snyder 1992). Considering Eq. (1), small error in prediction of K_{Pan} value may result in incorrect estimation of ET_0 value. Therefore, accurate prediction of K_{Pan} is essential for exact estimation of ET_0 value.

Roderick et al. (2007) used a 30-year time series of pan evaporation data (E_{Pan}) at 41 Australian sites. They reported a decreasing trend for E_{Pan} mostly due to decreasing wind speed and some regional contributions from decreasing solar radiation. Using an expanded anemometer network, McVicar et al. (2008) developed new grids for investigation of wind speed trend over Australia. Agreeing with earlier site-based studies, they reported a negative trend of about -0.009 m s^{-1} per year. Similar declines in pan evaporation records were also reported from USA, former Soviet Union, India, China, New Zealand and Canada. Roderick et al. (2009a, b) reported a decline in pan evaporation in terms of top-of atmosphere radiative forcing (-4.8 W m^{-2}) due to doubled CO_2.

There are several models to estimate K_{Pan}, all of them use mean daily data of wind speed (U), relative humidity (RH), and fetch length (F). Considering that pan coefficient values vary with climate conditions, it is necessary to determine the proper model for estimation of K_{Pan} in every interested climate (Conceição 2002).

Doorenbos and Pruitt (1977) reported a table with K_{Pan} values ranging from 0.40 to 0.85 and for various ground cover types surrounding the pan. Sentelhas and Folegatti (2003) estimated ET_0 values from class A pan evaporation data using different models to determine K_{Pan} for a semi-arid region in Brazil and compared these values with those measured by a weighing lysimeter. They indicated that the best K_{Pan} models to estimate ET_0 were Pereira et al. (1995) and Cuenca (1989) models. Gundekar et al. (2008) predicted ET_0 values using K_{Pan} models for a semi-arid region in India. By comparing with ET_0 calculated by the PMF-56 method, they found that the Snyder (1992) was the best K_{Pan} model for the semi-arid region.

The Penman–Monteith FAO 56 (PMF-56) model is a physically based model of energy interaction between vegetation and the atmosphere. It has been generally used to estimate evapotranspiration from plant fields. The PMF-56 model is a one-layer model that treats the canopy, including all leaves, and the soil surface as a 'Big Leaf'; it considers the vapor flux generated only from leaf stomata (Kato et al. 2004).

Although there are several models to estimate K_{Pan}, few are addressed their precision and accuracy under different climate conditions. Most of the models have shown that K_{Pan} value is highly dependent on surrounding conditions. The objective of this paper was to estimate ET_0 values from class A pan evaporation data using different K_{Pan} models and to compare the estimated ET_0 values with those obtained by the PMF-56 standard model for two different climate conditions in Iran. In addition, we determined a constant value of K_{Pan} as a simple and practical option to convert E_{Pan} into ET_0 for the mentioned climate conditions. Additionally, the annual trends of K_{Pan} and ET_0 values were also determined for the period of study. In this study, it is also assumed that pan coefficient is sensitive to the temporal variations and climate conditions.

2 Methodology

2.1 Site Locations and Data

In this study, effect of climate on K_{Pan} was considered for two different climates. Tabriz and Khoy synoptic stations as cold semi-arid climate and Yazd and Zahedan synoptic stations as warm arid climate were used (Table 1). The 10-years (1996–2005) daily meteorological data of: mean air temperature (T) in (°C), atmospheric relative humidity (%) (RH), pressure (P) (kPa), actual vapour pressure (e_a) in (kPa), net solar radiation (R_n) in (MJ m^{-2} day^{-1}), wind speed (U) in (m/s) and pan evaporation (E_{Pan}) (mm) were obtained from the stations. The monthly mean climatological variations of used parameters are shown in Fig. 1. Additionally, the annual trends of meteorological parameters are also shown in Fig. 2.

2.2 Pan Coefficient Models

We used seven models for estimation of K_{Pan} for the mentioned stations. The details of the relationships and their abbreviations are listed in Table 2. In the relationships (Table 2), U_2 is the mean daily wind speed measured at 2 m height (km day^{-1}), RH the mean daily relative humidity (%), F the upwind fetch distance of low-growing vegetation (m), Δ the slope of the vapor pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}). In this study, F was assumed 10 m (adopted from Sentelhas and Folegatti 2003). Note that the most of the seven pan models have been developed for arid and semi-arid conditions.

2.2.1 PMF-56 Model

In the present study, the PMF-56 standard method (Allen et al. 1998) was used to test the accuracy of the ET_0 estimated from K_{Pan} models (Eq. 2).

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T_a + 273} U_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \tag{2}$$

where R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T_a is the mean daily air temperature at 2 m height (°C), U_2 the wind speed at 2 m height (m s^{-1}), e_s the saturation vapor pressure (kPa), e_a the actual vapor pressure (kPa), Δ the slope of the vapor pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}).

Table 1 Geographical and climate conditions of the synoptic stations

Station	Longitude (E)	Latitude (N)	Elevation (m)	T(°C)	E_{Pan} (mm/year)	P (mm/year)	Climate type (Köppen)
Tabriz	46° 17′	38° 05′	1,361	13.7	3,230	235	Cold semi-arid
Khoy	44° 58′	38° 33′	1,103	12.9	2,102	246	Cold semi-arid
Yazd	54° 17′	31° 54′	1,237	20.3	3,968	53	Warm arid
Zahedan	60° 53′	29° 28′	1,370	19.2	3,829	66	Warm arid

T mean daily temperature, E_{Pan} mean annual pan evaporation, P mean annual precipitation

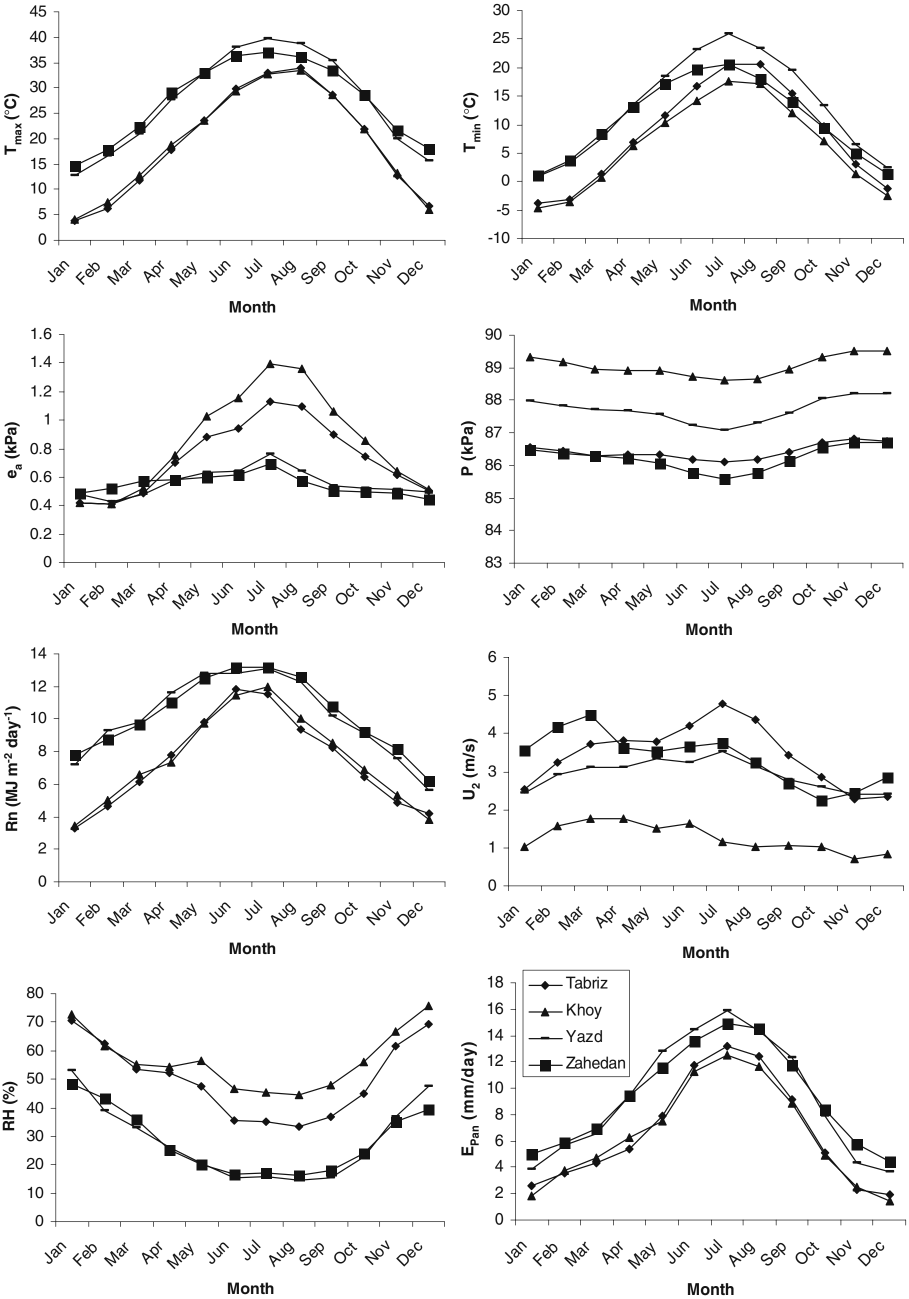

Fig. 1 Monthly means (1996–2005) of daily meteorological parameters averaged over 10 years

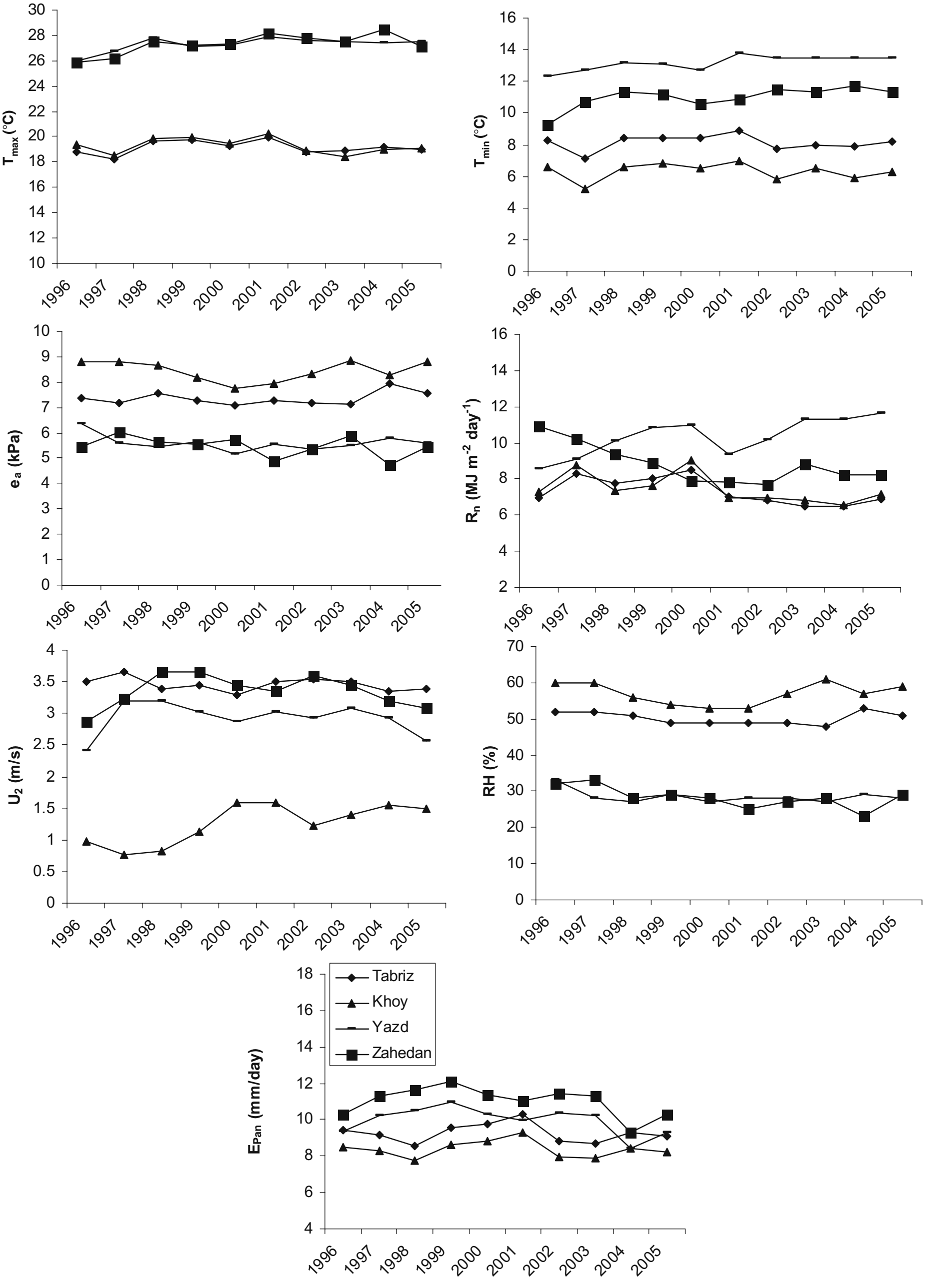

Fig. 2 Annual trends of meteorological parameters

2.3 Statistical Analysis

To evaluate the performance of the K_{Pan} models in daily ET_0 estimates, using the class A pan method (Eq. 1), several performance criteria were used including

Table 2 Details of different K_{Pan} models used in the study

Model	Abbreviation	Equation
Cuenca (1989)	C89	$K_{Pan} = 0.475 - (0.245 \times 10^{-3} U_2) + (0.516 \times 10^{-2} RH) + (0.118 \times 10^{-2} F) - (0.16 \times 10^{-4} RH^2) - (0.101 \times 10^{-5} F^2) - (0.8 \times 10^{-8} RH^2 U_2) - (0.1 \times 10^{-7} RH^2 F)$
Allen and Pruitt (1991)	AP91	$K_{Pan} = 0.108 - (3.31 \times 10^{-4} U_2) + (0.0422 Ln(F)) + (0.1434 Ln(RH)) - [6.31 \times 10^{-4} ((Ln(F))^2 Ln(RH))]$
Snyder (1992)	S92	$K_{Pan} = 0.482 + [0.24 Ln(F)] - (3.76 \times 10^{-4} U_2) + (0.0045 RH)$
Modified Snyder	MS92	$K_{Pan} = 0.5321 - (3 \times 10^{-4} U_2) + (0.0249 Ln(F)) + (0.0025 RH)$
Pereira et al. (1995)	P95	$K_{Pan} = 0.85 \times (\Delta + \gamma)/[\Delta + \gamma(1 + 0.33 U_2)]$
Raghuwanshi and Wallender (1998)	RW98	$K_{Pan} = 0.5944 + 0.0242 X_1 - 0.0583 X_2 - 0.1333 X_3 - 0.2083 X_4 + 0.0812 X_5 + 0.1344 X_6$ $X_1 = Ln(F), \begin{cases} X_2, X_3, X_4 = 0 & \text{if } U_2 < 175 \\ X_2 = 1 & \text{if } 175 \le U_2 < 425 \\ X_3 = 1 & \text{if } 425 \le U_2 < 700 \\ X_4 = 1 & \text{if } U_2 > 700\,(km/day) \end{cases}$ $\begin{cases} X_5, X_6 = 0 & \text{if } RH < 40\% \\ X_5 = 1 & \text{if } 40\% \le RH < 70\% \\ X_6 = 1 & \text{if } RH \ge 70\% \end{cases}$
Orang (1998)	O98	$K_{Pan} = 0.51206 - (0.000321 U_2) + (0.002889 RH) + (0.03188 Ln(F)) - (0.000107 RH\,Ln(F))$

All above K_{Pan} models were developed for arid and semi-arid regions

coefficient of determination (R^2), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Bias Error (MBE) and Jacovides criteria (t). The R^2 measures the degree to which two variables are linearly related and should optimally be one. The RMSE, MAE, MBE and t are criteria of the residual standard deviation and should be as small as possible (optimally zero). These criteria are defined is Eqs. (3)–(7), respectively.

$$R^2 = \frac{\left[\sum_{i=1}^{n} (X_i - \overline{X})(Y_i - \overline{Y})\right]^2}{\sum_{i=1}^{n} (X_i - \overline{X})^2 \sum_{i=1}^{n} (Y_i - \overline{Y})^2} \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_i - Y_i)^2}{n}} \tag{4}$$

$$MAE = \frac{\sum_{i=1}^{n} |X_i - Y_i|}{n} \tag{5}$$

$$MBE = \frac{\sum_{i=1}^{n} (X_i - Y_i)}{n} \tag{6}$$

$$t = \sqrt{\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}} \tag{7}$$

where X_i and Y_i are the ith observed and estimated values, respectively; $\overline{X}$ and $\overline{Y}$are the average of X_i and Y_i, and n is the total numbers of data.

3 Results and Discussion

3.1 Estimation of Pan Coefficient

Mean monthly values of K_{Pan} coefficients were computed using pan relationships (Table 2). In many irrigated areas, class A pans measurements are not supported with wind and relative humidity measurements. In such cases, the use of K_{Pan}–ET_0 method (Eq. 1) is an appropriate tool for estimation of pan coefficients. Mean monthly values of K_{Pan} (using seven pan models) were determined and compared with those obtained by the PMF-56 standard method (Eq. 1) for the two climate conditions (Fig. 3). Although, for the cold semi-arid sites, the results of annual mean K_{Pan} values are reasonable; nevertheless, the monthly mean estimates (Fig. 3a) do not perform good results. Gundekar et al. (2008) also found that Pereira model is not able to provide reasonable K_{Pan} estimates in semi-arid regions.

In addition, by using PMF-56 model, 10 years mean annual estimates of pan coefficient for the mentioned climates were determined and summarized in Table 3. As shown, the annual mean pan coefficients which estimated by means of the reference PMF-56 model for cold semi-arid and warm arid climates are 0.59 and 0.78, respectively, indicating that the mean annual values of pan coefficient for warm arid climate are approximately 32% higher than cold semi-arid climate. This is arises from the higher temperature, larger incoming solar radiation and increased evaporation rate in warm arid sites.

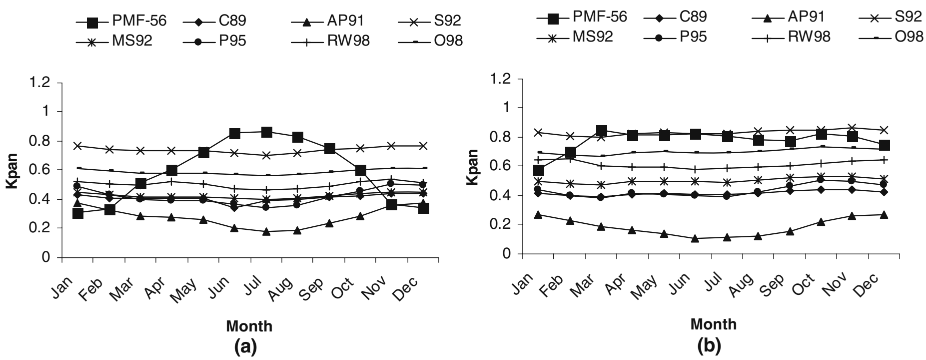

Fig. 3 Mean monthly K_{Pan} (1996–2005) calculated by PMF-56 method and using the K_{Pan} models for: **a** cold semi-arid climate, **b** warm arid climate

Table 3 Mean annual values of pan coefficients calculated by PMF-56 model for the two climates

Year	Cold semi-arid			Warm arid		
	ET_0(mm/day)	E_{Pan}(mm/day)	K_{Pan}	ET_0(mm/day)	E_{Pan}(mm/day)	K_{Pan}
1996	4.49	8.16	0.55	9.75	9.83	0.99
1997	4.51	8.30	0.54	8.92	10.79	0.83
1998	5.53	7.80	0.67	8.33	11.05	0.75
1999	5.71	7.90	0.68	7.94	11.53	0.69
2000	5.94	9.21	0.61	7.27	10.86	0.67
2001	5.39	8.74	0.58	8.78	10.52	0.83
2002	5.01	8.55	0.55	7.11	10.89	0.65
2003	5	7.68	0.61	7.57	10.73	0.71
2004	4.89	8.18	0.56	7.71	8.86	0.87
2005	5.17	8.37	0.58	7.56	9.81	0.77
Mean	4.87	8.29	0.59	8.09	10.49	0.78

3.2 Estimation of Daily ET_0

Table 4 presents the statistical analysis of ET_0 estimates using different pan models. In general, most of the pan models did not predict ET_0 values very accurately ($R^2 <$ 0.83). Similar results were reported by Sentelhas and Folegatti (2003). However, the deviations of some models such as Orang (O98), Raghuwanshi–Wallender (RW98) and Snyder (S92) are less than the other models.

For cold semi-arid climate condition, the best fitted K_{Pan} models to convert E_{Pan} into ET_0, were Orang (O98) and Raghuwanshi–Walender (RW98) models. Using the selected pan models, the relationship between ET_0 estimated using K_{Pan} models and determined by PMF-56 showed high accuracy and good precision as follows (Table 4): O98 model ($R^2 = 0.82$, MBE = 0.2, MAE = 0.9, RMSE = 1.7, $t = 6.7$ and Slope = 0.95); RW98 model ($R^2 = 0.81$, MBE = 0.3, MAE = 1.2, RMSE = 1.9, $t = 8.2$ and Slope = 0.91); S92 model ($R^2 = 0.81$, MBE = −0.3, MAE = 1.3, RMSE = 2.3, $t = 7.0$ and Slope = 1.11). Other models presented unacceptable performances, mainly when E_{Pan} was converted into ET_0 by the use of K_{Pan} obtained from Allen–Pruitt and Pereira models. Gundekar et al. (2008) also introduced O98 model as a proper model to estimate K_{Pan} for a semi-arid region in India. For the warm arid sites (Table 4) S92 model ($R^2 = 0.62$, MBE = −0.3, MAE = 1.4,

Table 4 Statistical analysis for the comparison between daily ET_0 estimated using different K_{Pan} models and calculated by PMF-56 for the two climates

Model	Cold semi-arid						Warm arid					
	R^2	MBE	MAE	RMSE	t	Slope	R^2	MBE	MAE	RMSE	t	Slope
C89	0.79	2.1	2.2	3.1	49.9	0.79	0.56	3.7	4.0	4.8	64.9	0.76
AP91	0.56	3.7	3.8	4.6	68.7	0.71	0.39	6.6	6.6	7.6	88.1	0.67
S92	0.81	−0.31	1.3	2.3	7.0	1.11	0.62	−0.3	1.4	2.5	7.6	1.08
MS92	0.80	1.3	1.7	2.4	34.6	0.84	0.58	2.8	3.1	4.0	51.1	0.81
P95	0.73	2.3	2.5	3.3	50.7	0.75	0.46	3.7	3.9	4.9	60.2	0.71
RW98	0.81	0.3	1.2	1.9	8.2	0.91	0.59	1.9	2.3	3.3	34.8	0.86
O98	0.82	0.2	0.9	1.7	6.7	0.95	0.61	0.41	1.6	2.6	7.9	0.89

MBE, MAE and RMSE are in mm day^{-1}

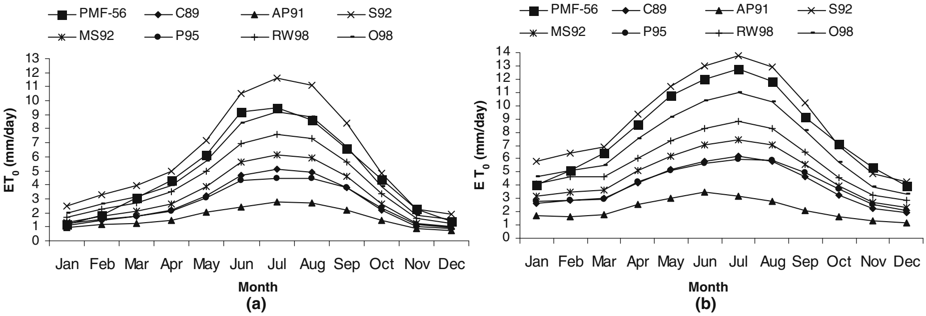

Fig. 4 Comparison of the mean monthly values of ET_0 estimated by PMF-56 method and using the K_{Pan} models (1996–2005) for: **a** cold semi-arid climate, **b** warm arid climate

RMSE = 2.5, t = 7.6 and Slope = 1.08) and O98 model (R^2 = 0.61, MBE = 0.41, MAE = 1.6, RMSE = 2.6, t = 7.9 and Slope = 0.89) presented the best estimates, respectively. In contrast, the Allen–Pruitt (AP91) and Pereira (P95) models presented the worse performance to estimate ET_0 for this climate.

3.3 Estimation of Monthly and Annual ET_0

Figure 4a and b compare the mean monthly ET_0 estimated by the K_{Pan} models and the calculated values by PMF-56 for the mentioned climates. As indicated, mean monthly ET_0 estimated by O98, RW98 and S92 models are nearly close to those obtained by PMF-56 method, whereas AP91, P95 and C89 models provided unacceptable estimations. A comparison between ET_0values estimated using K_{Pan} models and computed by PMF-56 method, denotes that with the exception of S92 model, all the mentioned pan models underestimate ET_0 in the two study climates.

Comparison of the mean annual values of ET_0 estimated by pan models for the two climates (Fig. 4) showed that the mean annual value of ET_0 for warm arid climate was larger than that obtained for the cold semi-arid sites. Among the pan models used in this study, Allen–Pruitt model (AP91) showed the largest deviations in comparison with the reference PMF-56 values. Additionally, Table 5 compares the annual average totals reference evapotranspiration estimated by PMF-56 with the corresponding values determined by pan models. It is shown that the mean annual value of ET_0 estimated by the selected S92 model for warm arid climate was 47% more than that obtained (by O98 model) for the cold semi-arid climate. The data is applicable for water resource management professionals.

For the applications of irrigation scheduling community and operational irrigation systems, the annual means and annual trends of pan coefficients which estimated by the best recommended K_{Pan} models (O98, RW98, S92) for the two climate types are

Table 5 Comparison of annual mean total (mm year^{-1}) ET_0 values (1996–2005) as estimated by PMF-56 method and the K_{Pan} models

Climate	C98	AP91	S92	MS92	P95	RW98	O98	PMF-56
Cold semi-arid	982	606	2,205	1,186	949	1,486	1,752	1,778
Warm arid	1,453	807	3,223	1,752	1,486	2,110	2,573	2,953

Table 6 The annual averages and annual trends of the best fitted K_{Pan} models for the cold semi-arid and warm arid climates

Statistics	Cold semi-arid					Warm arid				
	ET_0 (mm day^{-1})	E_{pan} (mm day^{-1})	K_{Pan} (PMF-56)	K_{Pan} (O98)	K_{Pan} (RW98)	ET_0 (mm day^{-1})	E_{pan} (mm day^{-1})	K_{Pan} (PMF-56)	K_{Pan} (S92)	K_{Pan} (O98)
Average	4.87	8.29	0.59	0.589	0.504	8.09	10.49	0.78	0.833	0.702
Trend (year^{-1})	0.0211	0.0117	−0.0019	0.0004	−0.0009	−0.1998	−0.1064	−0.0113	−0.0002	−0.001

shown in Table 6. The K_{Pan} trends indicate that climate conditions and climate trends could have some impact on the estimated K_{Pan} and ET_0 values.

4 Conclusions

This paper conducted to evaluate seven existing pan models (Cuenca; Snyder; Pereira; Allen–Pruitt; Modified Snyder; and Raghuwanshi–Wallender Models). Using a 10-year class A pan daily evaporation data (E_{Pan}) and the estimated K_{Pan} coefficients, reference crop evapotranspiration (ET_0) were predicted for the period of study. The deduced ET_0 values were compared to the corresponding ET_0 values which obtained from the standard Penman–Monteith FAO 56 (PMF-56) method. The statistical criteria (R, RMSE, MAE, MBE, t) indicated that the K_{Pan} values which estimated by most of the pan models, were not statistically accurate to be applicable in pan-ET_0 conversion method. However, the Orang (O98) and Raghuwanshi–Wallender (RW98) pan models performed the best results for cold semi-arid climate conditions. The results also showed that the estimated pan coefficients are more accurate in cold semi-arid sites. It was found that Snyder (S92) and Orang (O98) pan models are the most appropriate candidates for estimation of K_{Pan} in warm arid regions. The comparison of the mean annual K_{Pan} deduced for warm arid sites (by PMF-56 reference method) were approximately 32% larger than the corresponding K_{Pan} coefficients derived for cold semi-arid sites. Although, in this work the PMF-56 evapotranspiration model was considered as the reference standard method for evaluation of the estimated ET_0 data, the use of field lysimeter data might suggest more reliable estimates as future works. For investigation of climatic trends in K_{Pan} and ET_0 values, longer period of meteorological data is recommended.

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